# A STUDY OF A LIQUID METAL
# THERMAL ENERGY SOURCE

Final Report

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Liquid Metal Combustor

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

    A study of combustor systems for the lithium-sulfurhexafluoride
reaction combination is described.  The objective of the study was to
develop a combustor which could operate as a thermal energy source for
long periods with variable thermal power levels.  Several combustor
concepts were examined, including:  batch combustors with submerged
injectors, steady combustors with submerged injectors, wall-mounted wick
combustors and the reactive-heat-pipe.  The reactive-heat-pipe was found ——

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to be the most attractive system to meet program objectives. This concept involves reacting lithium from one side of a wick while employing the other side as the evaporator of a heat pipe. The energy of reaction is transported to the load heat exchanger by the heat pipe portion of the system. Reactive-heat-pipes were operated for extended periods, over variable thermal load cycles. The systems exhibited good fuel utilization; compactness; fast response to load changes; wick power densities on the order of MW per sq. m; restart capability; and uniform heat exchanger temperatures, even with large heat flux variations over the surface. Methods were also developed for refueling combustors.

# A Study of a Liquid Metal Thermal Energy Source

## Summary

This investigation considered the development of a combustor system based on the chemical reaction between gaseous sulfurhexafluoride and molten lithium. Numerous studies have shown that this reactant combination has great potential as a chemical thermal energy source for underwater applications. In combination with a closed heat-power cycle, such as a Rankine or Brayton cycle, the system provides a totally sealed mechanical power source.

The objective of the investigation was to develop a combustor system for long duration, variable load operation. Additional requirements were as follows: compactness, long term idling, complete shut-down and restart after an arbitrary storage period, reuse of the combustor and refueling capabilities, fast response to load changes and fast start, and good reliability and safety.

Several combustor concepts were developed to meet these objectives, as follows: batch-type combustor with submerged injector, steady combustor with submerged injector, wall-mounted wick-type combustor, and the reactive-heat-pipe. Combustors were designed for each configuration and extensively tested in order to establish operating characteristics. From the results of these tests, the reactive-heat-pipe proved to be the most promising arrangement for meeting program objectives.

The reactive-heat-pipe involves the combustion of lithium with $SF_6$ on one side of a wick, while using the other side of the wick as the evaporator of a heat pipe. The heat of reaction is conducted through the wick, causing lithium to evaporate from the outside surface. The lithium vapor then flows to the load heat exchanger and condenses to transfer the reaction energy to the load. The condensed lithium then is returned to the fuel inventory for either reuse in the heat pipe or combustion.

Reactive-heat-pipes were routinely operated for periods of 4-5 h, over variable load cycles. Methods of restarting after storage periods of up to one week were demonstrated. Combustors were routinely refueled. The reactive-heat-pipe also exhibited fast response to load changes. Since heat is transferred by vapor condensation, heat exchanger temperatures are very uniform, simplifying heat exchanger design. Arterial wick designs with reaction rate capabilities in excess of $1MW/m^2$ of wick area (wick power density) are possible with this system, and the operation of reactive-heat-pipes with arterial wicks was demonstrated.

Further study of several aspects of reactive-heat-pipe operation is needed before practical designs can be contemplated. High $SF_6$ flow rates into the reaction space can result in grossly nonuniform reaction rates over the inside surface of the wick, which limits the allowable power density of the system. The effect of wick geometry on reaction nonuniformity should receive further study if full system potential is to be achieved. More work is required to develop ignitor systems for fast start and restart. System durability could be improved by the use of high temperature alloys, and the long term compatability of these materials with lithium and its combustion products when reacted with $SF_6$ ($Li_2S$ and $LiF$) should be studied. Improved methods of $SF_6$ injector cooling are needed.

This final report summarizes the results of all aspects of the investigation. Further details may be found in other interim reports and papers generated during the study (References 1-11).

v

## Acknowledgement

## TABLE OF CONTENTS

## TABLE OF CONTENTS

viii

## LIST OF TABLES

## LIST OF FIGURES

# A STUDY OF A LIQUID METAL THERMAL ENERGY SOURCE

## Final Report

## 1. Introduction

### 1.1 Scope

This report summarizes an investigation of a liquid metal thermal energy source based on the chemical reaction between molten lithium and gaseous sulfurhexafluoride. This combustion system can provide the heat required to operate a closed thermodynamic cycle, such as a Rankine or Brayton cycle, to generate mechanical power. The reactant combination has a high energy density and since the combustion products are condensable they do not have to be removed from the combustor. Therefore, the combustor can operate totally sealed. These characteristics are very desirable for underwater power and propulsion systems, which is the main area of application of the Li-SF$_6$ combustion concept.

The investigation extended over the period of September 1, 1973 to June 30, 1978. The present report provides only a brief overview of the activities undertaken during the study. Further details may be found in Interim Reports and papers completed during the study [1-11]*. The initial phases of the study, under a different contract, are described in Ref. 12.

### 1.2 Objectives

The use of the Li-SF$_6$ reactant combination as a heat source for underwater applications was first proposed by Pauluikonis [13]. The potential of the system has been examined numerous times. Van der Sluijs [14] provides a recent survey of reactant combinations useful for underwater power systems, concluding that Li-SF$_6$ is superior to other reactants. These advantages were not missed by other workers, and numerous studies of Li-SF$_6$ combustion and power systems for use in underwater power applications, have been reported [15-19].

Early studies of Li-SF$_6$ power systems concentrated on short duration missions, with operating times less than one hour and simple load cycles [12]. The objective of the present investigation was to extend this technology to long duration missions; operating over infinitely variable loads (from idle to full power), including periods of total shutdown, followed by restart after an arbitrary period of time; with the capability for reusing the system after a refueling operation. The system must also exhibit adequate safety characteristics to allow operation in a manned, confined, environment.

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*Numbers in brackets denote references at end of report.

These are demanding requirements, and several different combustion systems were evaluated to determine whether they could meet program objectives. This included batch combustors, where all the fuel required for the mission and the products of combustion are stored within the combustor itself; and steady combustors, where fuel and product storage are separated from the reaction space. In both cases, designs were considered which could be refueled. Various methods of conducting the combustion process were also considered, as follows:

1. Batch combustor with submerged injector [1, 12].

2. Steady combustor with submerged injector [4, 9].

3. Wall-mounted wick combustor [5, 7].

4. Reactive-heat-pipe combustor [6, 7, 10, 11].

This report begins with a brief description of the characteristics of the reactants and the various combustion concepts. The results of the investigation for each concept are then discussed. The report concludes with recommendations, designating the systems with the greatest potential for meeting program objectives. An assessment of areas which require further investigation before practical applications can be considered is also included.

## 2. Reaction Concepts

### 2.1 Reaction Characteristics

The stoichiometric equation for the Li-SF$_6$ reaction is

$$8Li + SF_6 \rightarrow 6LiF + Li_2S$$
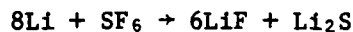
The oxidizer (SF$_6$) is nontoxic, and can be stored as a liquid under its own vapor pressure at room temperature (21.8 bar at 20C [1]). The oxidizer enters the combustion chamber as a gas and reacts with liquid lithium. The lithium fluoride and lithium sulfide produced by reaction are liquids which are soluble in each other at typical combustor operating temperatures (1100-1400K). The product liquid has a slightly smaller volume than the volume of the original fuel at combustor temperatures [4], and can be stored with the fuel. The product liquid is immiscible with liquid lithium, and due to its greater density, separates into a layer below the fuel.

The theoretical energy release of the reaction is 4.75kW/hr/kg of oxidizer, at combustor temperature levels [4]. The energy of reaction is transferred to the power cycle by heat exchangers located on the surface or within the combustion chamber.

The combustion process is initiated by melting the lithium, and then introducing the oxidizer. Heating is accomplished by electrical heater coils, for restartable systems, or by solid propellant charges, for single-start systems. Once ignited, the rate of thermal energy release is controlled by varying the oxidizer flow rate. Reaction can continue until the fuel is consumed. Typically, more than 95% of the lithium can be consumed in practical combustor arrangements. The reaction can be stopped prior to complete fuel consumption by terminating the flow of oxidizer.

## 2.2 Batch Combustor with Submerged Injector

The batch combustor using a submerged injector is pictured schematically in Fig. 1. This arrangement was used in the initial development of the Li-SF$_6$ combustion concept, and still finds application for short duration operation [20-24].

The oxidizer enters the combustor through an injector whose outlet is below the surface of the liquid. Reaction occurs in a two-phase turbulent jet originating from the exit of the injector. The characteristics of this jet have been studied and methods are available for predicting the jet penetration length, etc. [8]. The products of reaction settle through the bath and collect in an immiscible liquid layer at the bottom of the combustor. As reaction proceeds, the product level rises, until the consumption of the lithium is complete. When the lithium concentration of the bath is low, the oxidizer bubbles to the surface, pressurizing the ullage space. This rise in pressure signals the end of combustion and operation can then be terminated by discontinuing the flow of oxidizer.

The heat of reaction is transferred to the heat exchanger surfaces, through the bath. The stirring action of the injector assists the heat transfer process.

Initial work to develop long duration Li-SF$_6$ combustors employed the submerged injector concept [12]. However, problems were encountered with injector operation at low oxidizer flow rates. The injector was primarily cooled by the oxidizer flow, and low flow rates lead to overheating and corrosion. A second problem involved injector clogging at low flow rates.

These injector problems were circumvented by the development of the coaxial injector illustrated in Fig. 2 [1]. In this arrangement, the oxidizer flows through a central passageway, surrounded by a coaxial flow of argon in an outer concentric shroud passage. The shroud flow prevents the liquid from clogging the passage, even at low flow rates of SF$_6$. The oxidizer flow can also be terminated and restarted.

The arrangement of a combustor using a coaxial injector is illustrated in Fig. 3. The argon flow is not large [1], but must be recirculated in practical systems. This involves venting the argon from the combustor, cooling it, removing condensed lithium and product vapors, and recompressing the flow for reuse in the injector. The recirculation system increases the complexity of the combustor, which reduces reliability.
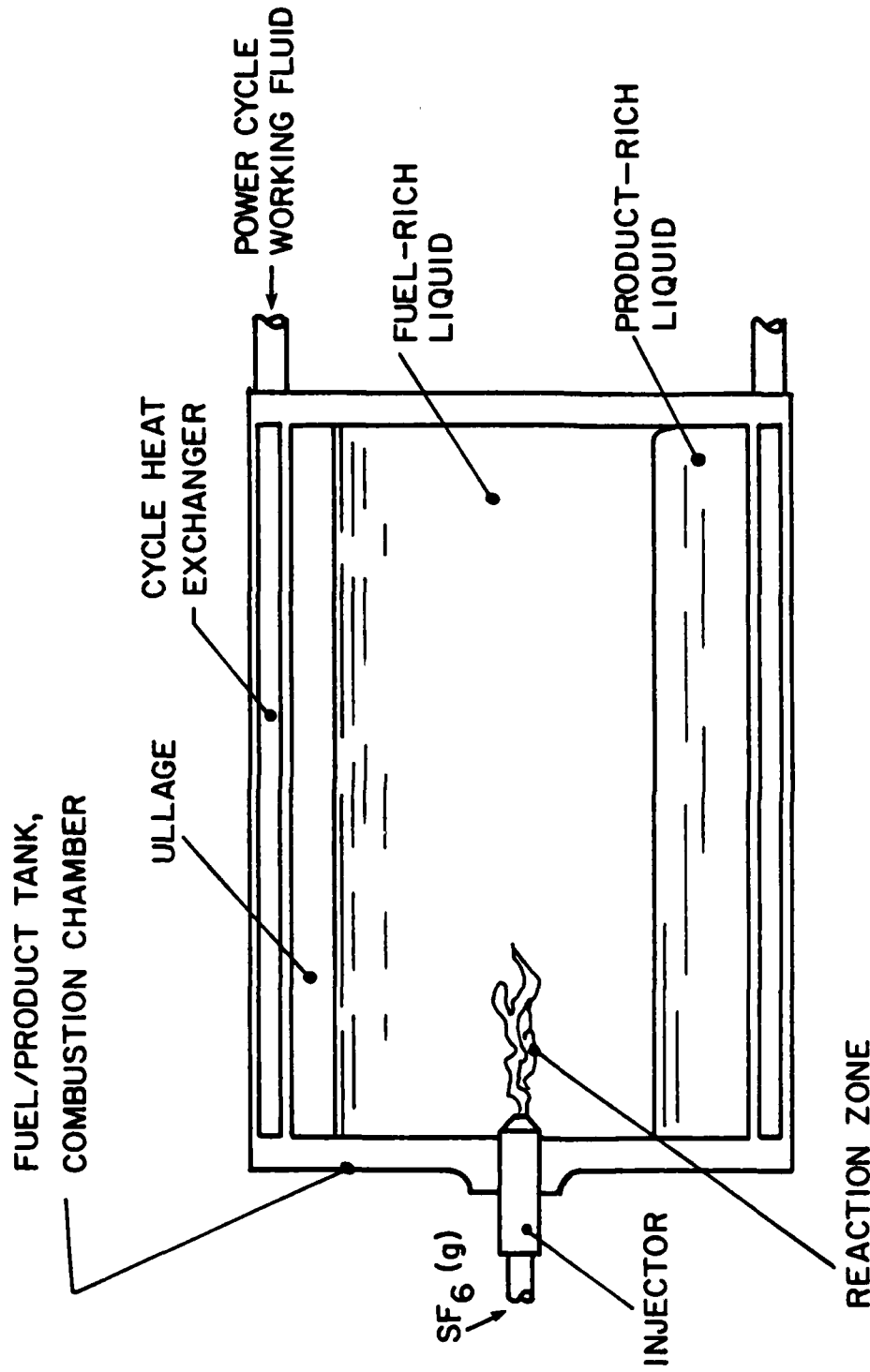
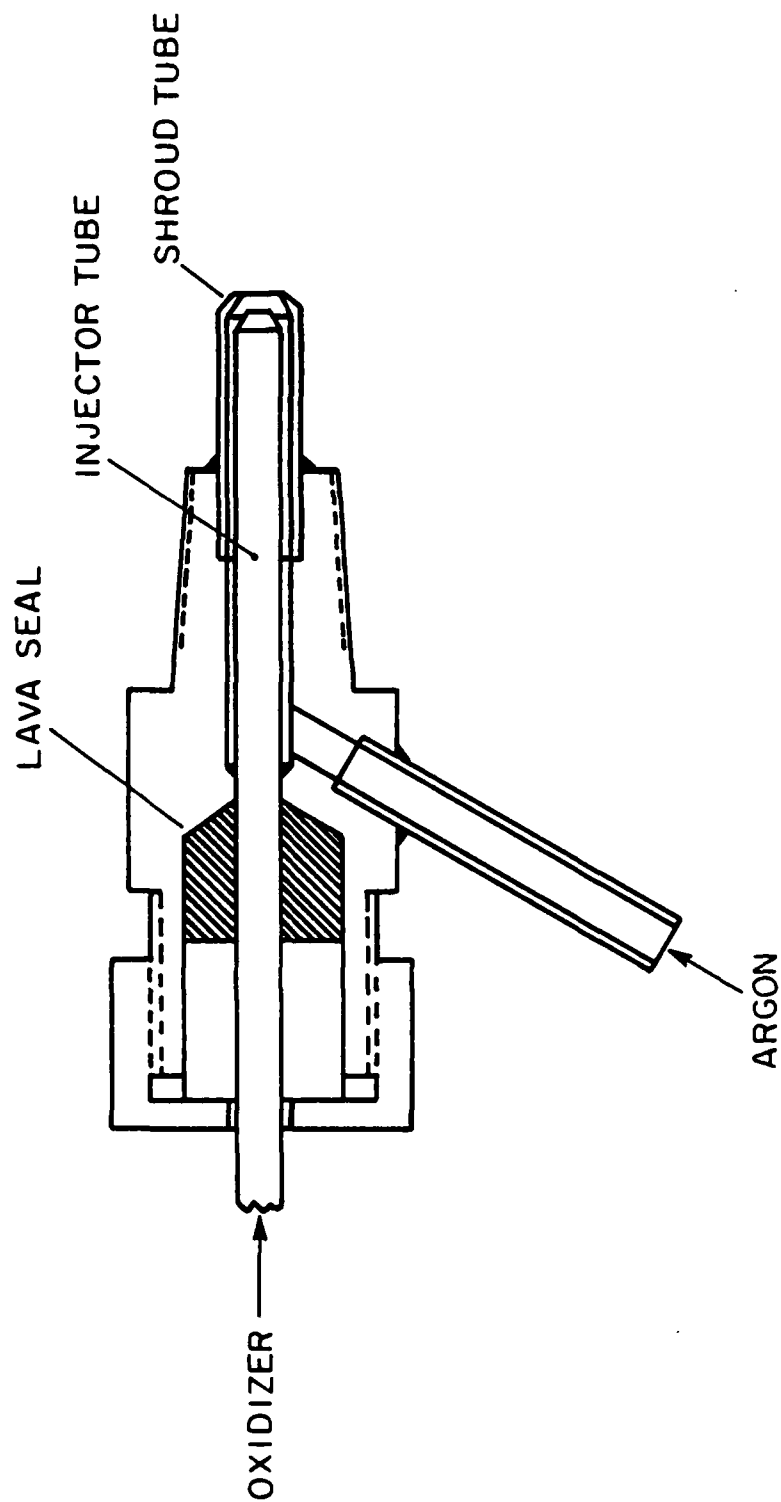Figure 1  Sketch of a batch combustor using a submerged injector.

Figure 2  Sketch of the coaxial injector
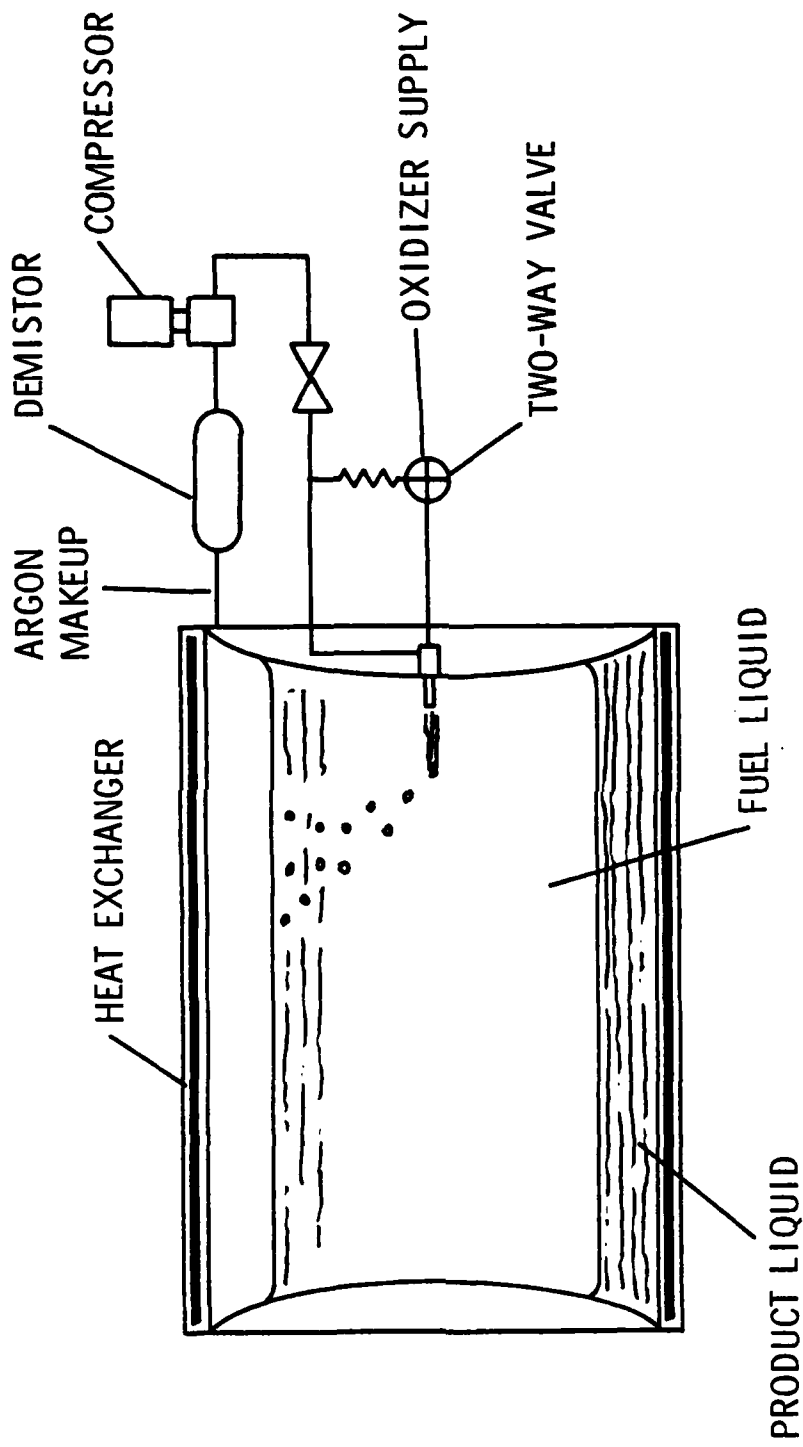
Figure 3  Sketch of a batch combustor using a coaxial injector

A second problem that was encountered with submerged injector systems involved the relatively poor heat transfer characteristics of the stratified product layer at the bottom of the combustor. As the layer increases in height, the performance of the heat exchanger is decreased, creating problems in the design of heat exchanger components. The temperature of the bath must vary as the load changes. This introduces response problems due to the large thermal capacity of the bath liquids.

## 2.3 Steady Combustor with Submerged Injector

Since the product liquid and lithium are immiscible, and the product has a higher density, it is a relatively simple matter to remove the product through a trap to provide a steady combustor configuration. The steady combustor concept is illustrated in Fig. 4.

Fuel and oxidizer both flow into the combustor while product liquid is removed in a continuous fashion. Minor imbalances of the fuel/oxidizer mass flow ratio are absorbed by adjustment of the liquid level in the ullage space of the combustor. For the most compact system, the product liquid is returned to the fuel storage tank. The configuration can operate using any of the combustor concepts that are discussed in the report, since trapping the flow of product is always possible. During the present investigation, however, only the coaxial submerged injector system was considered in actual tests of steady combustors.

The steady combustor provides improved heat transfer characteristics since the trap can be designed so that the product layer does not contact the heat exchanger surfaces. The response to load changes is improved as well. The good heat transfer characteristics of lithium result in relatively small temperature differences between the bath and the heat exchanger surfaces for most designs, reducing the need for large bath temperature changes when the load is varied. The thermal capacity of the combustor is also reduced, since it only contains a portion of the total fuel inventory.

## 2.4 Wall-Mounted Wick Combustor

Both injector and heat exchanger response problems can be reduced by employing combustors where the lithium is burned from a wick which is in contact with a gas containing $SF_6$. This concept was initially described by Uhleman, et al [16]. A sketch of a typical arrangement appears in Fig. 5.

Lithium flows from the bath through a wick which is attached to the heat exchanger surfaces. The reaction occurs in the gas space adjacent to the wick. The reaction occurs as a diffusion flame, fed by oxidizer flowing through the injector and lithium evaporating from the wick.

Figure 4 Steady combustor concept
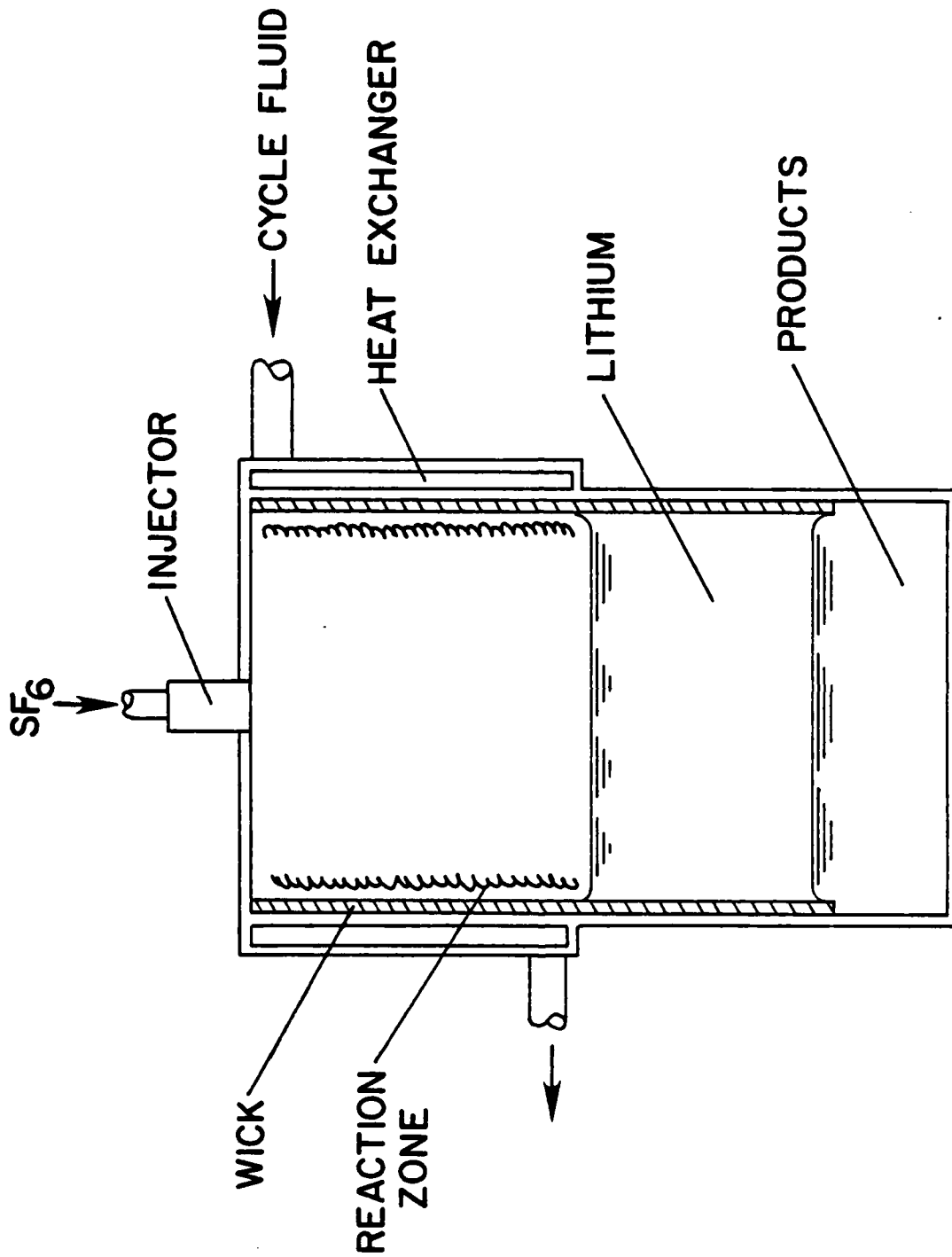
Figure 5  Wall-mounted wick combustor

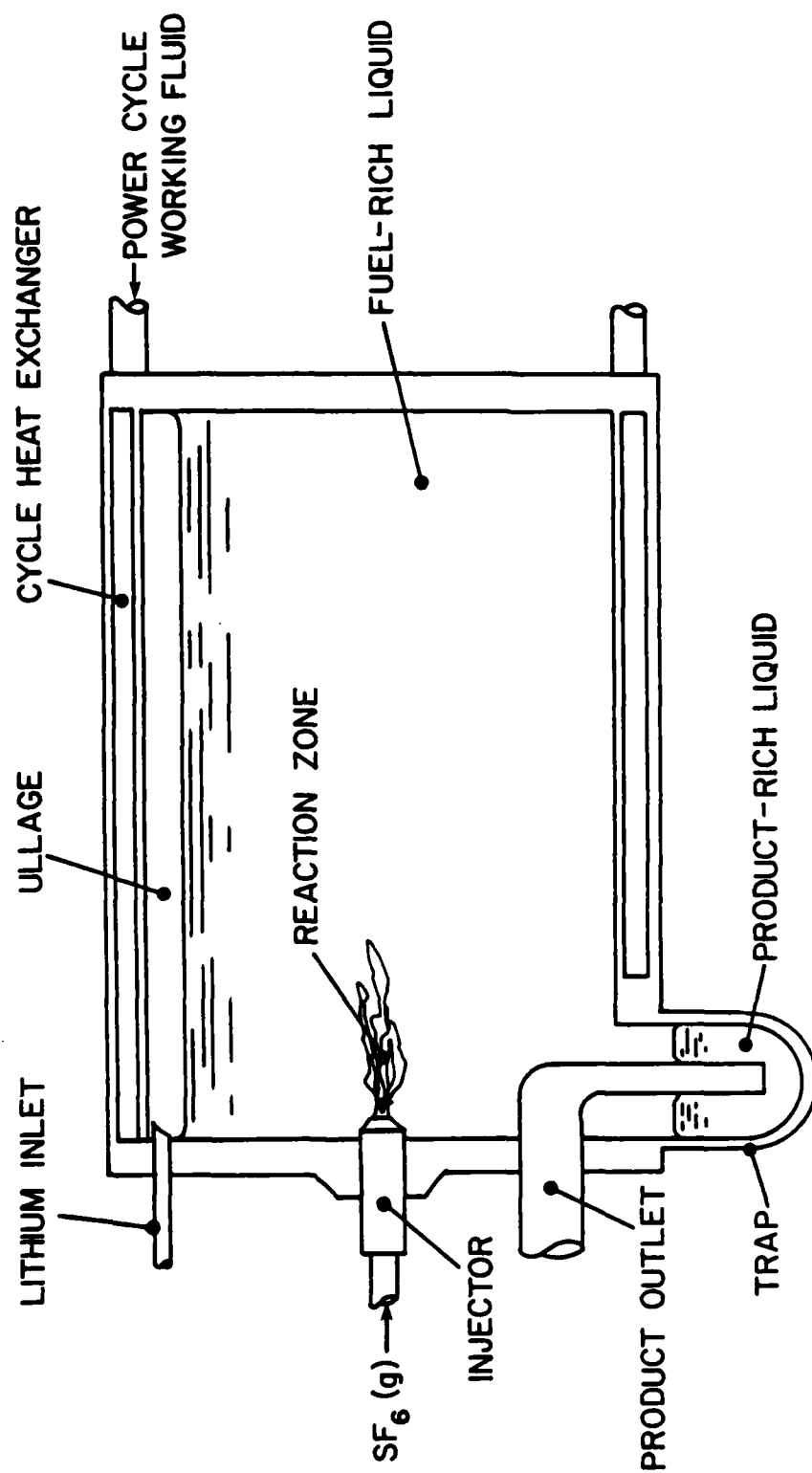The details of the wick combustion process have been studied by Blakeslee and Faeth [5]. It was found that the combustion products that formed in the flame, condensed on the wick and drained back into the bath. Since the liquids are immiscible, dropwise condensation occurs, and lithium evaporation is not impeded to a great degree by the presence of condensed product. When noncondensible materials are not present in the system, the pressure in the reaction space is fixed by the vapor pressure of lithium at the surface temperature of the wick [5]. This pressure is relatively low at typical operating conditions, on the order of 0.01 bar.

The heat of reaction is transferred through the wick to the heat exchanger surfaces. Since this region is not influenced by the height of the product layer, heat transfer characteristics do not vary as the lithium is consumed. Response to load changes is rapid, since only the thermal capacity of the wick region is involved. Injector problems are minimized with this arrangement since the lithium is confined to the wick, in the region of the injector, reducing the potential for clogging. Injector cooling is also simplified.

The wall-mounted wick arrangement is generally not as compact as submerged injector designs. Completely covering the heat exchanger surfaces with wicking also presents fabrication problems.

### 2.5 Reactive-Heat-Pipe Combustor

The reactive-heat-pipe concept was developed under the present contract [5, 6, 7, 10]. This system combines the features of the wick combustor and a heat pipe. The heat pipe portion of the system is used to transfer the energy of reaction to the load. The reactive-heat-pipe concept is illustrated in Fig. 6.

The wick is free-standing in the reaction vessel, attached at its upper end to the top of the combustion chamber, and opening into the bath at the bottom. The oxidizer is injected into the space enclosed by the wick and the bath. Reaction is confined within this volume, and proceeds in the same manner as the wall-mounted wick arrangement.

The energy of reaction is conducted through the wick, causing lithium to evaporate from the outside surface. The lithium vapor then flows to the heat exchanger surfaces, where it condenses to complete the transfer of reaction energy. The condensate drains back into the molten bath within the combustor. Thus the region outside the wick acts like a heat pipe.

Since heat is conducted through the wick, the temperature on the inside surface is higher than the outside surface. Therefore, the vapor pressure in the reaction space is higher than the heat pipe region, resulting in a pressure difference across the wick. This pressure difference is accomodated by a displacement of the liquid level under the reaction zone. Since lithium vapor pressures are low at typical combustor operating conditions, the liquid displacement is not large (generally on the order of 10-20 mm).
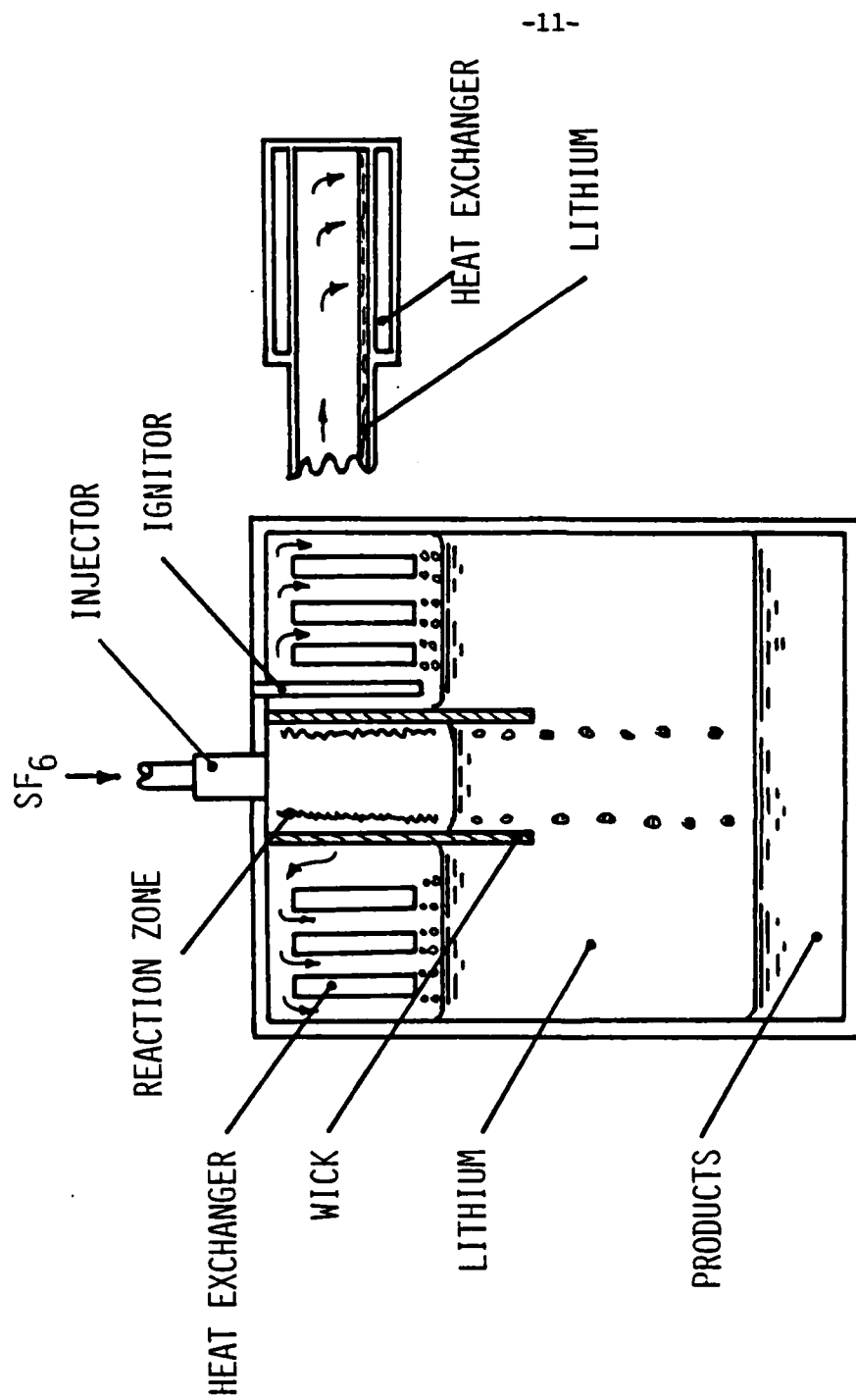
Figure 6  Reactive-heat-pipe combustor

The reactive-heat-pipe concept provides a relatively uncomplicated design which simplifies wick installation. Heat pipe action provides uniform temperatures on the load heat exchanger, simplifying the design of this component. The system is more compact than the wall-mounted wick arrangement, since the ullage region can be utilized by the heat exchanger.

## 3. Batch Combustors with Submerged Injectors

### 3.1 Introduction

The initial phases of the investigation continued work on submerged injector combustors that began in an earlier study [12]. The present investigation considered coaxial injector systems, while the earlier study was largely devoted to single passage injectors.

An extensive series of tests were conducted to develop various aspects of the coaxial injector system; the injector, the vent, etc. These tests employed radiatively cooled combustors, where the heat exchanger was simulated by heat loss from the body of the combustor to the surrounding test cell. Work was also undertaken to design, fabricate and test a combustor for use as the heater of a closed Brayton cycle engine that had been developed by AiResearch Manufacturing Corporation. Activities in both of these areas are described in the following.

### 3.2 Developmental Tests

#### 3.2.1 Test Combustors

Initial tests with the coaxial injector system were conducted with a small combustor containing about 1 kg of fuel. This preliminary system is described in Ref. 1.

The bulk of the developmental tests were conducted using radiatively cooled combustors, having the configuration shown in Fig. 7. Table 1 is a summary of the major features of these designs.

The combustor was mounted with the top surface permanently insulated. The insulation on the sides and bottom, however, was wrapped around a movable heat shroud which fits around the combustor. The heat shroud was mounted on a cable arrangement so that it could be moved up and down over the combustor body. The energy of combustion was transferred from the walls of the combustor by convection and radiation. Therefore, the position of the heat shroud could be used to control the rate of heat transfer from the combustor.
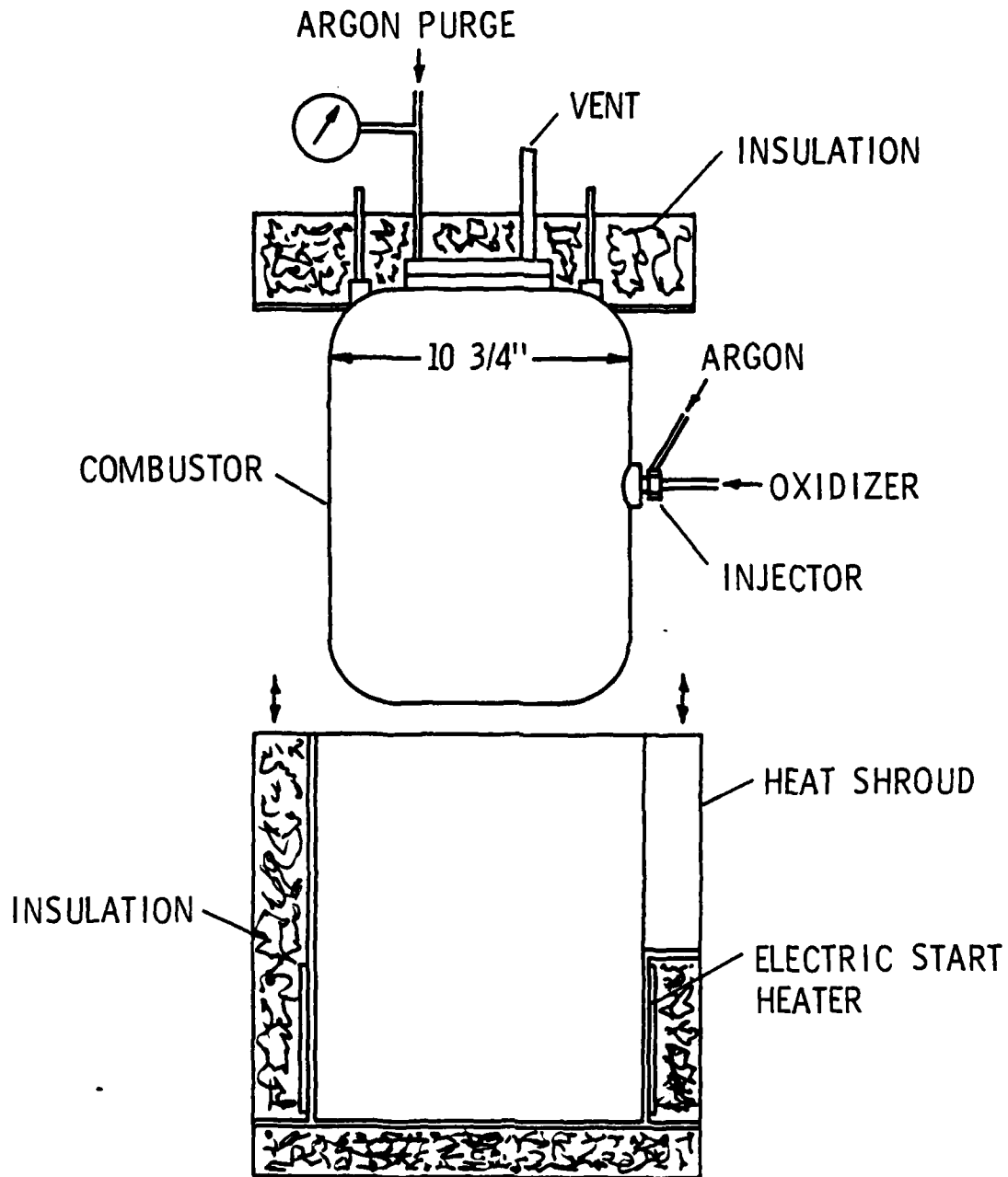
Figure 7   Radiatively cooled combustor

TABLE 1

Design Summary of Radiatively Cooled Combustor[a]

| | |
|---|---|
| Fuel Loading: | 6.8 kg |
| Oxidizer Required: | 17.9 kg |
| Combustor Dimensions: | 273 mm diameter, 422 mm long (uninsulated) |
| Internal Pressure: | Vented |
| Maximum Power: | 30–40 kW thermal |
| Materials: | Type 316 SS |

[a] A longer version containing 10.4 kg of fuel was also tested which had a maximum power level of 50 kW thermal.

Two combustor sizes were used, one containing 6.8 kg and the other containing 10.4 kg of fuel. The larger combustor could reach power levels of 50 kW thermal, which was about half the desired power level of the Brayton combustor.

The combustors were ignited by melting the fuel with an electric heater which was permanently mounted in the heat shroud. The heaters were also used to fuel the combustor. With the combustor heated to temperatures above the melting point of lithium, the fuel was added as solid lithium rods through the vent tube. The fuel subsequently melted within the combustor to form the fuel bath.

Argon and $SF_6$ were metered and fed to the injector through two separate lines. The flow path within the injector is illustrated in Fig. 2. The $SF_6$ was reacted in the bath. The argon bubbled to the surface and was removed through the vent. This flow passed through a baffle, and then after cooling in the vent line was filtered in order to remove the small particles formed by the condensation of lithium and product vapor.

Several methods of controlling the flow of $SF_6$ were examined. This included manual control and automatic control using the bath temperature as the control signal.

### 3.2.2 Summary of Test Results

Twenty-six tests were conducted with the radiatively cooled combustors. These tests are briefly summarized in Table 2, further details may be found in Ref. 1. In all cases, the combustor was ignited by heating the bath to 500-600 K and initiating the flow of $SF_6$. With adequate stirring of the bath by the flow of $SF_6$, ignition was immediate and the combustor could be brought to operating temperatures by a continued flow of $SF_6$. During heat-up, the heat shroud was fully closed.

Most tests were conducted using the thermal load cycle specified for the Brayton combustor. This load cycle is illustrated in Fig. 8 (only two hours of operation are shown, the cycle was to be repeated three times prior to terminating operation). A sample of the data for a typical test is illustrated in Fig. 9 (Test 10). For this test the flow of oxidizer was controlled automatically with an on-off controller. In periods when the oxidizer flow was off, the argon flow through the injector prevented back-flow of the bath into the injector passages and clogging.

Operating periods were generally over a single load cycle, with a total operating time on the order of 3 h. Long term operation was demonstrated in test 2, 17 h, and test 18 was conducted over the three prescribed load cycles. Combustors were reused many times. One unit achieved a total operating time of nearly 80 h, and was still reusable.

TABLE 2

Summary of Developmental Combustor Tests

| TEST | ARGON FLOW (kg/h) | SF$_6$ FLOW (kg/h) | MAX. BATH TEMP. (K) | RUN TIME (h) | REMARKS |
|------|-------------------|--------------------|---------------------|--------------|---------|
| 1 | 0.39 | 0.25-1.22 | 1180 | 4.6 | SS core tube plugged |
| 2 | 0.25 | 0.25-1.22 | 1210 | 17.0 | |
| 3 | 0.25 | 0.39-1.32 | 1290 | 8.0 | |
| 4 | 0.25 | 0-6.26 | 1230 | 3.2 | |
| 5 | 0.25-1.08 | 0-7.17 | 1230 | 3.0 | load cycle |
| 6 | 0.25-0.59 | 0-4.94 | 1290 | 3.0 | load cycle |
| 7 | 0.25-0.59 | 0-7.67 | 1240 | 3.0 | load cycle, 20% control |
| 8 | 0.25-0.91 | 0-6.0 | 1210 | 3.0 | load cycle, 40% control |
| 9 | 0.91-1.08 | 0-10.0 | 1210 | 3.1 | load cycle, controlled |
| 10 | 0.91 | 0-10.0 | 1220 | 2.7 | load cycle, controlled |
| 11 | 0.91 | 0-5.0 | 1260 | 2.5 | load cycle |
| 12 | 0.91 | 2.5 | | .3 | vent blockage |
| 13 | 0.91 | 0-10.0 | 1240 | 2.7 | load cycle, controlled |
| 14 | 0.91 | 0-10.0 | 1210 | .5 | vent blockage |
| 15 | 0.64 | 0-6.4 | 1250 | 2.7 | load cycle |
| 16 | 0.64 | 0-6.1 | 1220 | 2.5 | load cycle, controlled |
| 17 | 0.64 | 0-6.1 | 1240 | 3.7 | load cycle, controlled |
| 18 | 0.64 | 0-7.6 | 1260 | 7.0 | three load cycles |
| 19 | 0.91 | 0-2.9 | 1200 | 1.0 | |
| 20 | 0.91 | 0-7.9 | 1245 | 3.0 | load cycle, controlled |
| 21 | 0.41-.91 | 0.23-4.2 | 1200 | 1.9 | shakedown test |
| 22 | 1.13 | 0.59-2.45 | 1200 | 1.1 | Brayton injector |
| 23 | 0.04-1.36 | 1.50-6.49 | 1230 | 2.5 | |
| 24 | 0.45-0.91 | 0.41-6.40 | 1230 | 2.6 | |
| 25 | 0.95 | 0.41-3.32 | 1220 | 2.6 | product dump |
| 26 | 0.64-1.04 | 0.64-2.54 | 1270 | 2.8 | |
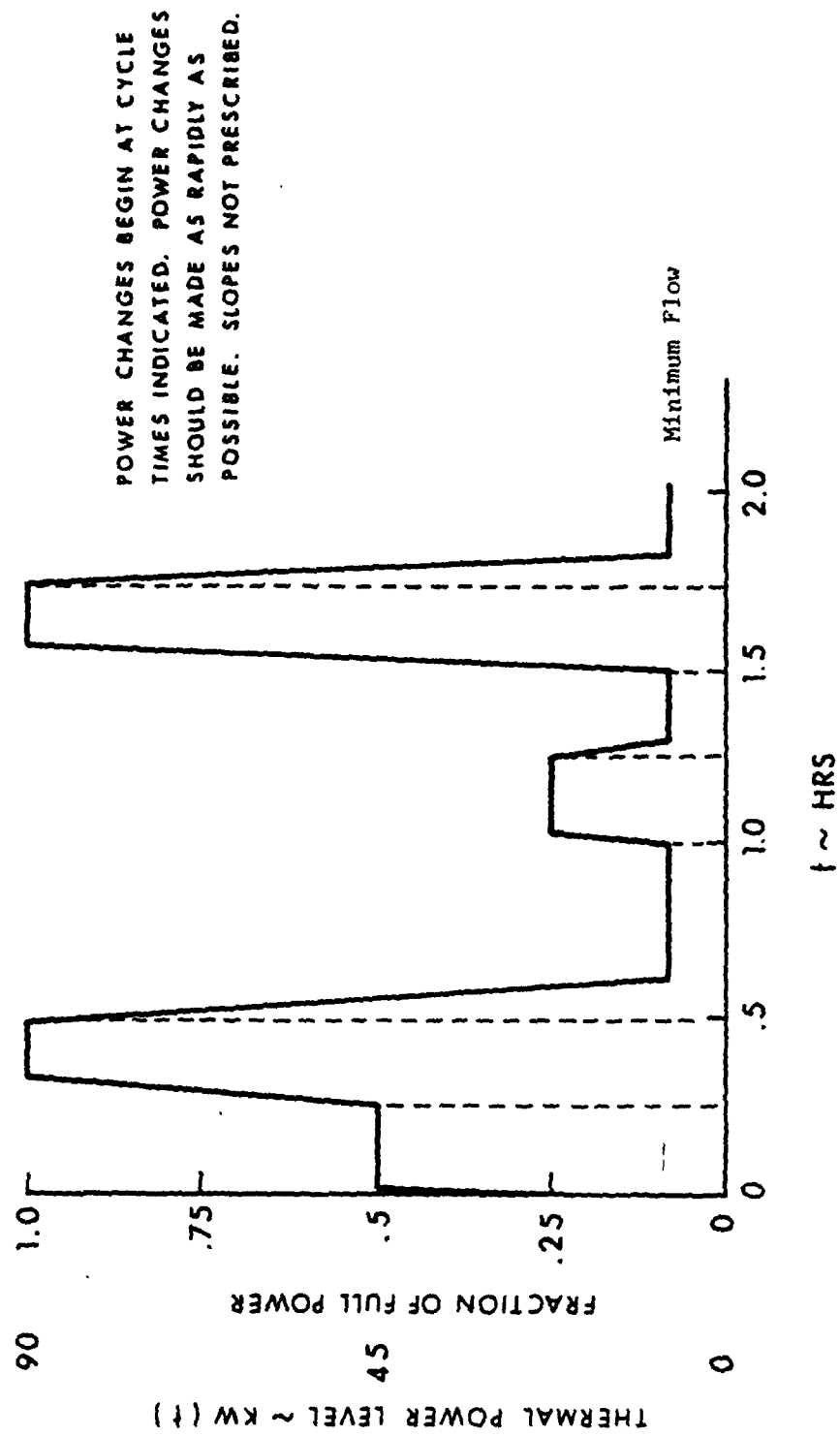
Figure 8   Power test cycle for Brayton combustor
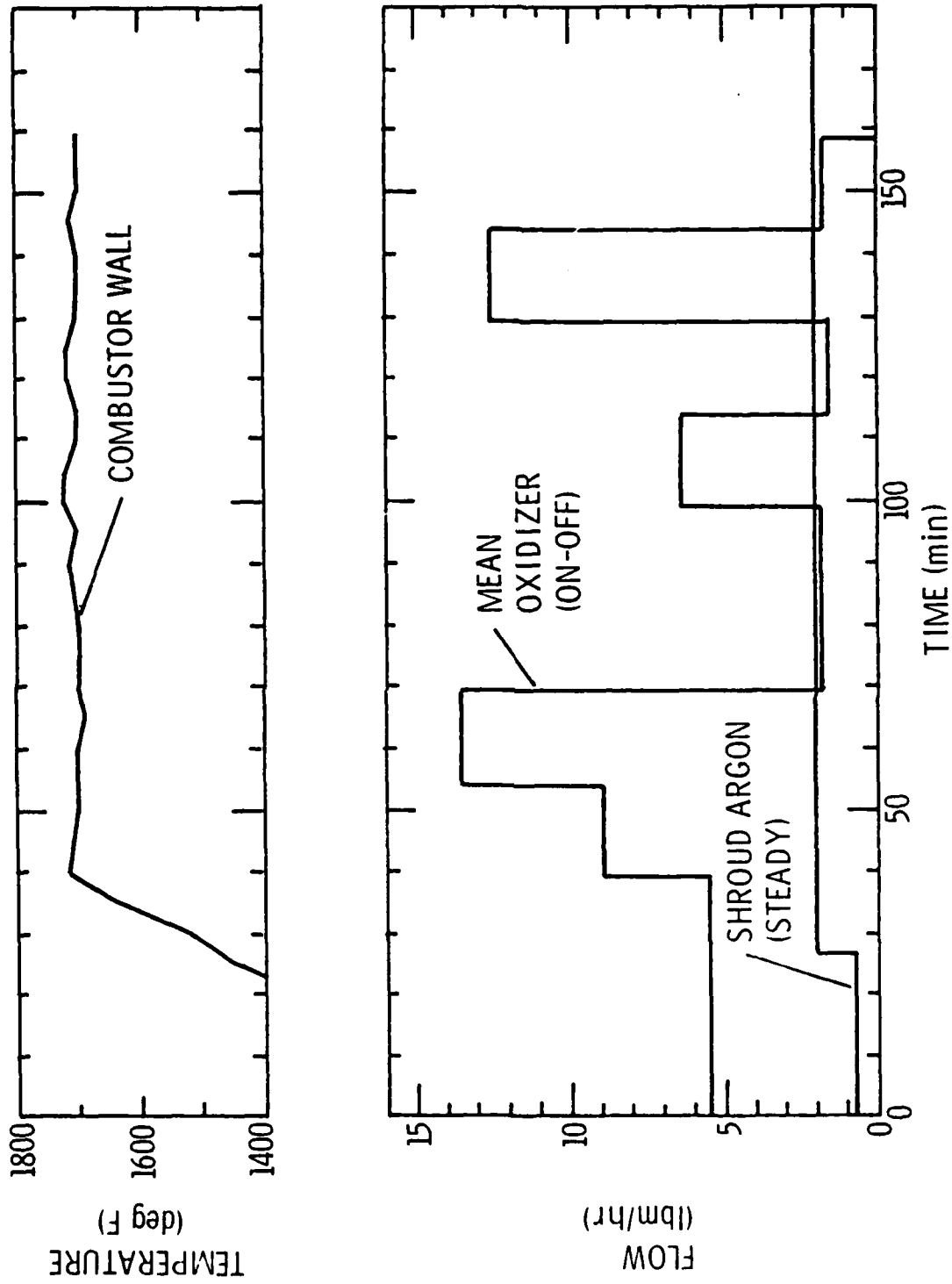
Figure 9  Typical submerged injector combustor test results

The coaxial injector demonstrated good reliability over the test range and could be operated in the on-off mode. The combustors could be shut-down and restarted. The combustors could also be refueled by melting the product and forcing it out of the combustor through a dip tube, by pressuring the liquid surface with argon.

A problem that was encountered involved excessive corrosion of the tip of the injector at high oxidizer flow rates and low argon flow rates. This condition caused flow separation in the injector passage. This allowed the $SF_6$ to contact the hot outer portions of the passage causing corrosion. Satisfactory operation could be maintained with argon flow rates on the order of 1 kg/h.

Various vent flow and baffle configurations were examined during the tests. It was found that negligible quantities of $SF_6$ carried over into the vent flow, except for a pulse at ignition.

The major difficulty with the coaxial injector system was the complexity of the argon recirculation system. A second problem was the poor heat transfer characteristics of the product layer at the bottom of the combustor. Heat transfer rates were quite low in this region, particularly when it was not stirred by the flow through the injector [1]. This stratified heat transfer pattern introduced significant design problems for the Brayton heat exchanger.

### 3.3  Brayton Combustor

The Brayton combustor was designed to act as the heater of a closed Brayton cycle engine developed by the AiResearch Manufacturing Corporation. A description of the engine may be found in Ref. 21.

#### 3.3.1  Combustor Description

A summary of the major design features of the Brayton combustor appears in Table 3. Figure 10 is a crosssectional view of the combustor. The combustor design included a number of features to provide operating flexibility with subsequent engine tests, including a capability for long idle periods and restart. The unit was to be operated over three consecutive load cycles of the type shown in Fig. 8.

The combustor was vented, with the shroud argon flow passing through a vent/demistor. Two injectors having the same design as those used for the developmental tests were employed.

The heat exchanger of the Brayton cycle was contained in the cylindrical side walls of the combustor, with inlet and outlet manifolds located at the top and the bottom. The heat exchanger employed circumferential fins (209 fins per metre). The cycle working fluid was argon. The outside surfaces of the combustor and manifold were insulated with Fiberfrax Low-Con Blanket (Union Carbide Corp.).

TABLE 3

Design Summary of Brayton Combustor

## COMBUSTOR SYSTEM

| | |
|---|---|
| Fuel Loading | 26.3–27.2 kg |
| Oxidizer Required | 69.2–72.5 kg |
| Energy Content | 330–340 kW-h |
| Bath Volume | 0.076 $m^3$ |
| Oxidizer Volume | 0.053 $m^3$ |
| Combustor Dimensions | 419 mm diameter, 867 mm long (uninsulated) |
| Volumetric Energy Density | 2.64 $MW/m^3$ |
| Internal Pressure | Vented |
| Combustor Weight | 117 kg |
| Maximum Cycle Power | 96.7 kW thermal |

## HEAT EXCHANGER

| | |
|---|---|
| Working Fluid | Argon |
| Flow Rate | 0.671 kg/s |
| Inlet and Outlet Temperature | 812 K, 1089 K |
| Inlet and Outlet Pressure | 485.8 kPa, 480.9 kPa |

## INJECTORS

| | |
|---|---|
| Type | Coaxial |
| Argon Flow | 1.09 kg/h |
| Oxidizer Flow | 0–10.6 kg/h |

## START SYSTEM

6 kW electrical resistance heater

## INSULATION

Fiberfrax Lo-Con Blanket (Carborundum Co.) 6lbm/cu ft, aluminum foil backing, 51 mm thick.

## REACTANTS

| | |
|---|---|
| Fuel | Lithium, Regular Sodium Content 99.8% purity |
| Oxidizer | $SF_6$, C. P. Grade, 99.8% purity |

## MATERIALS

| | |
|---|---|
| Combustor Body | RA330 |
| Injector Body | 316SS |
| Oxidizer Tube | Nickel 200 |

Figure 10  Modified Brayton combustor

The combustor was started in the same manner as the developmental units. The electrical heaters were located on the end walls and along the lower portions of the heat exchanger, under the insulation. While ignition was under manual control, subsequent operation employed the flow controller developed during the earlier test program [1].

In tests conducted here, the cycle fluid was simulated by a flow of oil-free air. The air flows were selected to cover the design operating range when used with argon. Two combustor units were fabricated.

### 3.3.2 Summary of Test Results

Initial tests with the combustor verified that the pressure drop through the heat exchanger satisfied specifications. The combustor was then fueled and tested.

Ignition was achieved at 505 K, and the combustor was heated to operating temperatures. After about an hour of operation, a problem was encountered with a temporary blockage of the vent due to splashing of liquid. During cool-down, a crack was also observed in the end plate.

The crack was found to be the result of improperly penetrated welds and the end caps were redesigned to improved weldability. A baffle assembly was also designed to prevent blockage of the vent.

When retested after these modifications, no further blockage problems were encountered indicating that the new baffle was adequate. However, difficulties continued to be encountered with cracks in the end plate welds. The combustors were subsequently shipped to David W. Taylor Naval Ship Research and Development Center for continued work on the fabrication difficulties. Fabrication problems were eventually resolved. Continued developmental activities under the present investigation turned to the more promising wick-type combustor systems and the units were not retested here.

### 3.4 Conclusions

The major conclusions of developmental study of batch-type combustors employing submerged injectors are as follows:

1. The use of single open passage injectors presents problems at low $SF_6$ flow rates due to injector corrosion and clogging.

2. The coaxial injector design resolves difficulties at low $SF_6$ flow rates. Sporadic corrosion was encountered at high $SF_6$ flow rates due to flow separation in the injector passages. This problem could be overcome by increasing the argon flow rate, however, this approach amplifies problems of recirculating the argon flow.

3. Argon recirculation was demonstrated, however, this system is rather complex, reducing reliability. Attention must be given to careful baffle design around the vent, to prevent slugs of bath liquid from entering the recirculation system. Except at start, negligible amounts of $SF_6$ are found in the vent flow.

4. Tests demonstrated restart capability as well as refueling methods. Total combustor operating times were in excess of 70 hours, comprising over twenty cycles to operating temperatures from room temperature, with no significant levels of corrosion of combustor materials.

## 4. Steady Combustor

### 4.1 Introduction

The problem areas in the development of the steady combustor concept involved evaluating methods of continuous fuel addition and combustion product removal, demonstrating long term system operation, and determining combustor performance in terms of both fuel utilization and chemical energy release.

Since the steady combustor can provide stable bath conditions for extended periods of time, the tests were also used to obtain measurements of bath properties. This included bath densities and compositions as a function of temperature. The rational correlation of this data was undertaken by developing a thermodynamic model to discribe the properties of the immiscible liquid system formed by lithium, lithium fluoride and lithium sulfide.

A complete discussion of the findings of this portion of the investigation may be found in Refs. 1, 4 and 9.

### 4.2 Test Apparatus

Two steady combustors were examined during the study. A radiative combustor was employed for measurements of bath liquid density. A larger, air-cooled combustor was used to study the entire operation of the system and to generate data on bath compositions and thermal performance.

The radiative combustor is described elsewhere [4], a sketch of the air-cooled combustor appears in Fig. 11. The combustor employed a coaxial, submerged injector. The heat exchanger consisted of an annular passage around the combustor body, through which a metered flow of oil-free air was passed. The combustor body was 260 mm in diameter and 483 mm long.
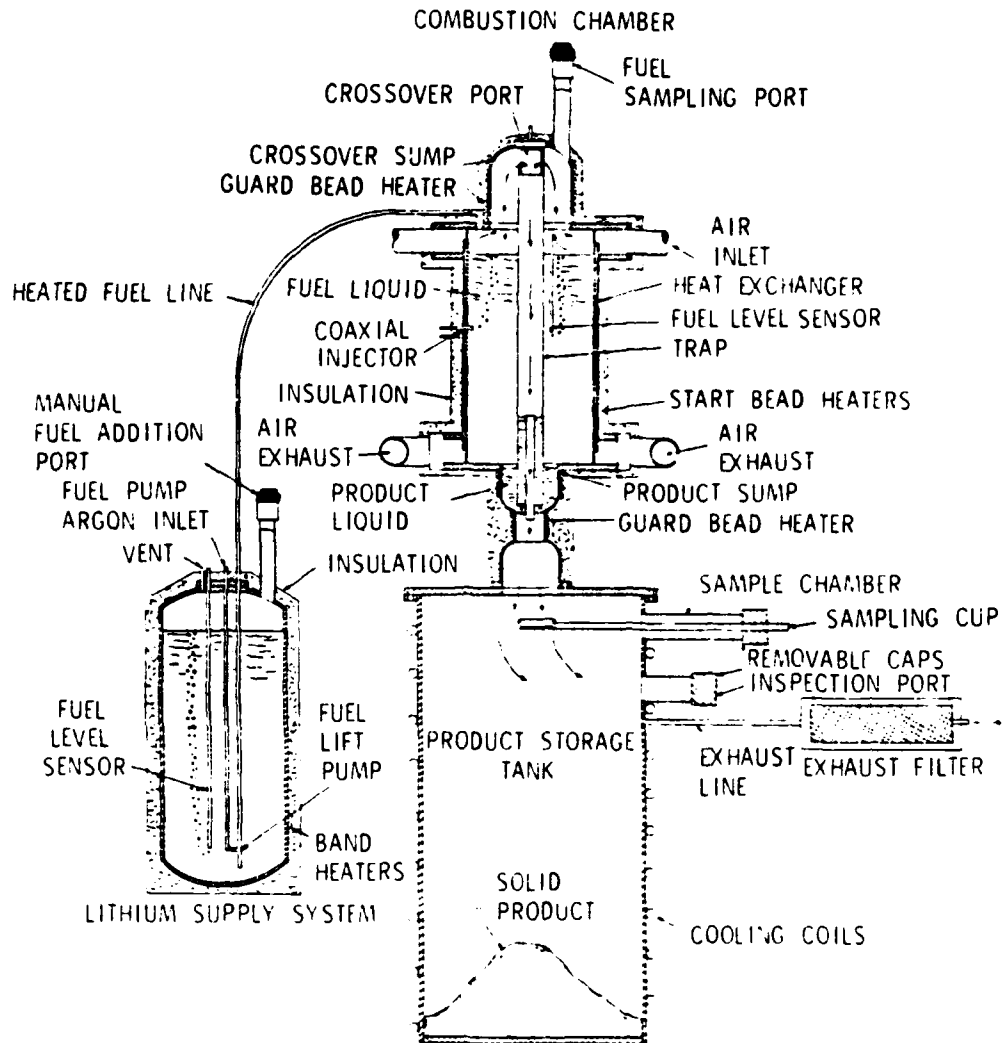
Figure 11  Steady combustor arrangement

The product-rich liquid was collected in a sump at the bottom of the combustor, and passed out through a trap into a product storage tank. No attempt was made to combine the fuel and product storage areas, since it was desired to obtain uncontaminated samples of the product as it left the combustor. The sump in the combustor insured that the heat exchanger only contacted liquid metal, to provide optimum heat transfer characteristics.

The argon flow from the coaxial injector also passed out the trap. After flowing through the product storage tank, the argon was filtered to remove lithium condensate and exhausted.

The fuel tank was filled by adding lithium rods through a port at the top. The fuel tank was heated to maintain the lithium as a liquid. The lithium was transferred to the combustion chamber by a lift pump, which employed argon as the driving gas. During operation, a steady flow of lithium was maintained into the combustor, with periodic flow rate adjustment to keep liquid levels relatively constant. Liquid levels were determined by measuring the pressure at the exit of bubblers.

Liquid samples could be drawn from both the fuel-rich and product-rich portions of the bath, through argon purged ports. Bath compositions were determined by wet-test chemical analysis procedures [4]. The power level was measured from the air flow rate and temperature rise through the heat exchanger. Combustor operation was started by melting the lithium in the combustion chamber and then initiating a flow of $SF_6$ through the injector. The product in the sump was maintained molten by an electrical guard heater.

### 4.3  Test Results

A summary of the steady combustor tests is given in Table 4. Eight tests were conducted with the radiatively cooled combustor, ten tests were conducted with the air cooled unit. Both combustors were in good condition following the tests, which was typical for 316SS components throughout the entire investigation. Most of the tests had a duration of 3-10 h, depending upon test objectives. Power levels were in the range 4-25 kW, and bath temperatures as high as 1300 K were considered.

Figure 12 is an illustration of test data taken with the air-cooled combustor (test 10). During this test, measurements of thermal performance were obtained and a progressive sequence of power increases and decreases were studied. Combustor temperatures were maintained relatively constant, the heat loss was adjusted by varying the flow rate of cooling air.

The test results indicated that the thermodynamic model described in Ref. 4 predicted bath compositions and thermal performance with good accuracy. The product-rich liquid only contained 0.2-1% (molar) lithium, increasing with temperature. This implies a fuel utilization efficiency of 99% for the steady combustor. The fuel-rich liquid is largely lithium (greater than 95% on a molar basis). The density of the product-rich liquid is 3.2-3.4 times larger than the lithium rich liquid, decreasing

TABLE 4

Summary of Steady Combustor Tests

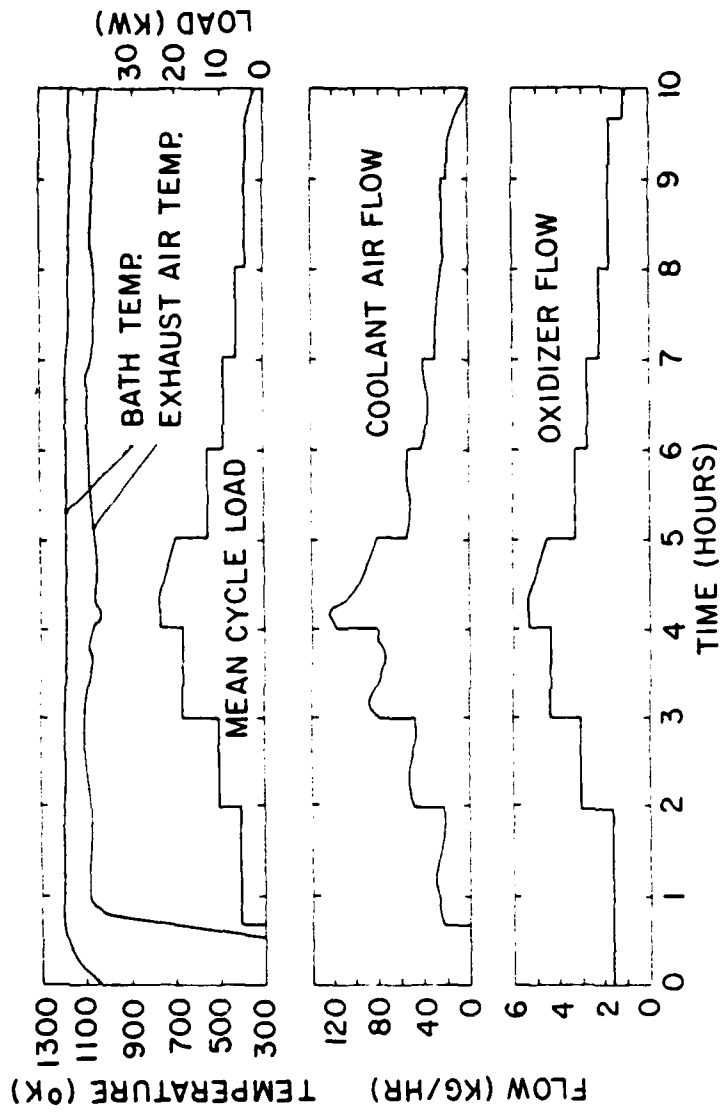| TEST | DURATION (h) | MAXIMUM BATH TEMP. (K) | MAXIMUM POWER (kW) |
|------|--------------|------------------------|--------------------|
| Radiatively Cooled Combustor | | | |
| 1 | 2.0 | 1264 | 5.8 |
| 2 | 1.5 | 1261 | 5.8 |
| 3 | 7.1 | 1233 | 4.2 |
| 4 | 1.3 | 1177 | 4.2 |
| 5 | 7.1 | 1272 | 4.5 |
| 6 | 5.6 | 1219 | 10.7 |
| 7 | 3.2 | 1297 | 3.9 |
| 8 | 4.5 | 1252 | 13.2 |
| Air Cooled Combustor | | | |
| 1 | 2.4 | 1208 | 10.8 |
| 2 | 2.6 | 1213 | 10.8 |
| 3 | 1.4 | 1225 | 10.8 |
| 4 | 3.8 | 1210 | 10.7 |
| 5 | 2.5 | 1172 | 8.9 |
| 6 | 0.9 | 1161 | 3.6 |
| 7 | 2.8 | 1238 | 5.4 |
| 8 | 5.2 | 1255 | 5.4 |
| 9 | 6.3 | 1205 | 23.6 |
| 10 | 10.0 | 1205 | 25.2 |

Figure 12  Typical steady combustor test results

with increasing temperature. This large density ratio is a desirable feature since rather large variations of the lithium level in the combustor can be accomodated by relatively small product level changes in the trap. For steady operation at 1200 K, the thermal energy release was 4.99 kW-h/kg of $SF_6$ (fuel at 533 K, $SF_6$ at 298 K) in comparison to the predicted value of 4.75 kW-h/kg.

Testing with these configurations was relatively routine. The combustors could be refueled indefinitely, and restarting after extended storage periods (weeks) was demonstrated numerous times.

### 4.4 Conclusions

The feasibility of the steady combustor was demonstrated in the temperature range 1100-1300 K. Single periods of operation extended up to 10 h. Less than 1%, on a molar basis, of lithium is carried out of the bath with the products, providing good fuel utilization even when the products are not returned to the fuel storage tank. More than 83% of the standard heat of reaction at 298 K, or 4.75 kW-h/kg of $SF_6$, can be transferred to the load for combustor temperatures near 1200 K.

The lithium-rich portion of the bath has a molar concentration of lithium greater than 95%. The high concentration of liquid metal in this portion of the bath provides relatively uniform bath temperatures and good heat transfer characteristics.

Test durations during the investigation were relatively short in comparison to the endurance objectives of long-term thermal energy sources. Over the periods observed, however, corrosion or deterioration of the combustor, that would prohibit larger running periods, were not encountered.

## 5. Wall-Mounted Wick Combustors

### 5.1 Introduction

The wall-mounted wick combustor for the $Li-SF_6$ reactant combination was first described in Refs. 16 and 17. In this area, the objectives of the present investigation were as follows:

1. Observe the operation of the combustor and establish design procedures for the wick.

2. Determine the characteristics of the reaction process, e.g. the pressure within the reaction space and the rate of reaction over the wick surface.

3. Examine the effect of system geometry on performance and long-term operation.

The details of this portion of the investigation are reported in Refs. 5 and 7. These findings indicated the feasibility of the reactive-heat-pipe concept, and the bulk of the effort on wick-type combustors during this investigation was devoted to the latter area.

## 5.2 Test Apparatus

Several wall-mounted wick combustors were examined during the study. A sketch of a typical combustor appears in Fig. 13. Table 5 is a summary of the major design features of the combustors that were tested.

The combustors were made of type 316 stainless steel, except for a nickel 200 injector flow passage. Nickel 200 was used in the injector area due to its high resistance to corrosion by fluorine compounds [22].

The combustor wicks were made of type 316 stainless steel woven wire cloth. Standard heat pipe design procedures were used to choose mesh sizes, number of layers of mesh, etc. [23]. The design analysis used in the present case is described elsewhere [7]. The wicks were spot-welded to the walls of the combustor.

All the combustors were radiatively cooled, with either a movable heat shield or a capability of varying insulation thickness employed to vary the rate of heat transfer. The active portion of the heat exchanger consisted of the region adjacent to the wick surface, above the liquid level in the combustor.

The injectors employed a passive cooling system. This consisted of an enlarged cylindrically shaped section, adjacent to the point of attachment of the injector to the combustor. Heat was drawn up the injector walls and rejected from the cylindrical surface by radiation and convection.

The combustors were ignited by heating with electrical coils mounted under the insulation. Ignition was generally achieved by heating to 920 K and admitting the $SF_6$ to the reaction space. Ignition at lower temperatures was not examined during the investigation.

The $SF_6$ flow was metered with critical flow orifices. The flow rate was varied by controlling the pressure level at the upstream side of the orifice with a pressure regulator. Provision was also made for filling the combustor with argon, to prevent contamination with air during assembly. The combustor could also be evacuated with a vacuum pump. Since the system generally operated under a vacuum, all connections were either welded or brazed to prevent leakage of air into the combustor. A leak detector was employed to insure vacuum integrity.
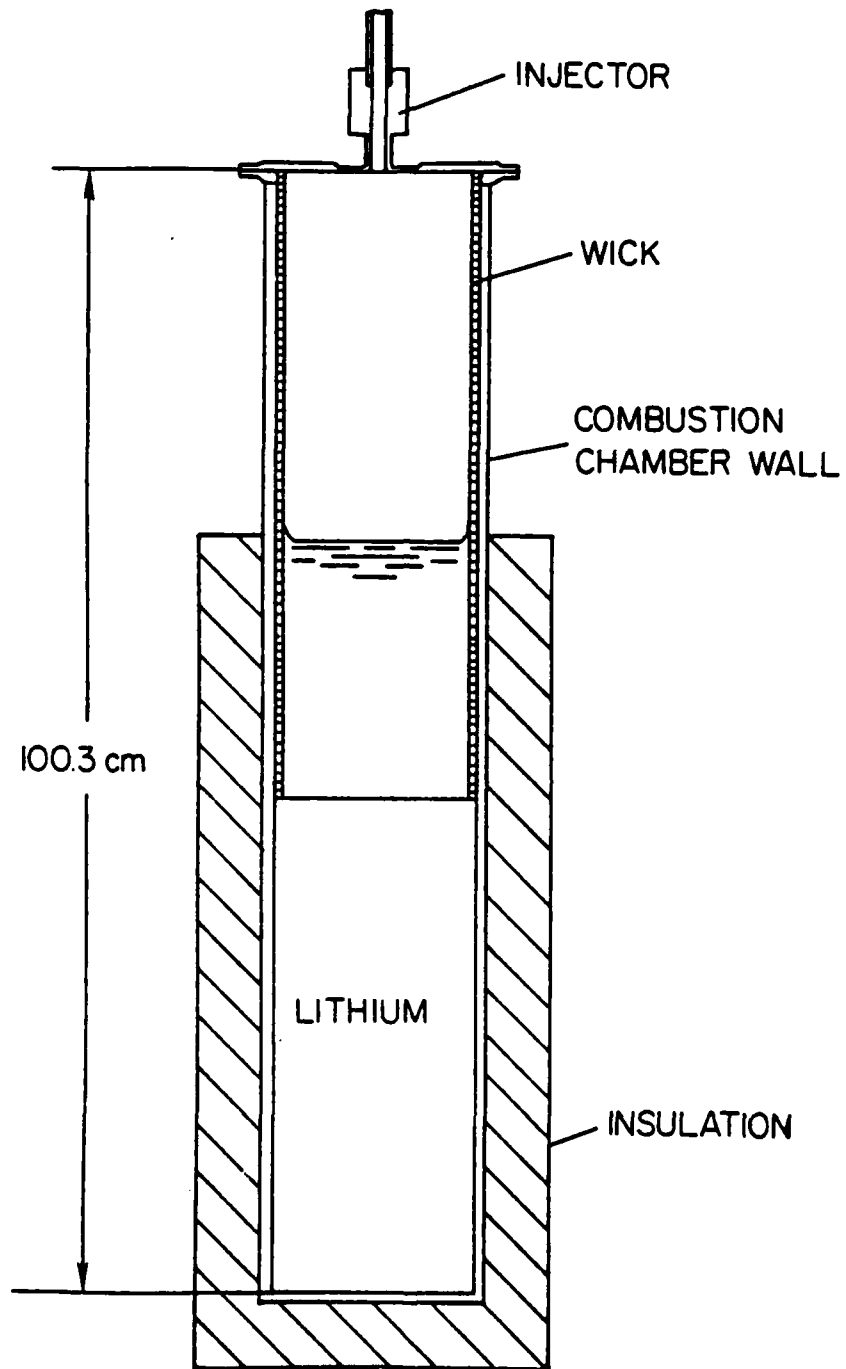
Figure 13  Wall-mounted wick combustor arrangement

Temperatures were measured by spot-welding chromel-alumel thermocouples over the surface of the combustor. Combustor pressures were measured at the inlet of the injector. For the conditions of the tests, the pressure drop through the injector was negligibly small, providing a valid reading at this position [5, 7].

The combustors were filled with lithium rod, prior to welding the top in place. Filling was done under argon in a dry-box. After the combustor was assembled into the apparatus, the fuel was degassed (lithium normally contains some dissolved argon as a result of manufacturing procedures) and the wick was wetted. This was done by heating the assembly to 850 K, under vacuum, and then continuing the heating to 1100 K with the injector sealed. After the system had cooled below 850 K, vacuum pumping was continued until the unit was tested.

## 5.3 Test Results

The tests conducted with the wall-mounted wick combustors are summarized in Table 6. Sixteen tests were conducted with the various units. Combustors A and B had small fuel inventories and tests with these units were relatively short. Combustor C was used for long term tests. In particular tests 14, 15 and 16 should be noted. These were accomplished with one fuel loading, by restarting the combustor, yielding a total operating time of nearly one day. The combustor was stored for about a week between each of these tests. These results indicate the flexible operational capabilities of the wick-type combustors.

The highest wick power densities achieved during the tests (defined as the rate of heat transfer per unit area through the active portion of the wick) was 213 kW/m$^2$. This limit was set largely by the heat transfer characteristics of the combustor surface, and does not represent an operating limit of the wick designs.

High fuel utilization was not examined for every test. However, fuel utilization in excess of 93% was obtained, whenever high fuel utilization was sought. Fuel utilization was somewhat lower when a combustor was restarted and then run to completion. This was due to fuel being trapped in the product layer formed during the initial test(s).

Inspection of the combustor after testing revealed no deterioration of the combustor body or the wick.

Tests of these combustors showed a definite relationship between the combustor pressure and the temperature of the inside surface of the wick. These results are illustrated in Fig. 14. In addition to the test results, predictions of the vapor pressure of lithium as a function of temperature are also shown [5]. Except at the lowest pressures, where the data can be more influenced by low levels of noncondensibles in the system, the combustor pressure is essentially equal to the vapor pressure at the wick surface temperature. The surface temperature-combustor pressure relationship is also independent of the rate of reaction (or heat flux) of the wick.

TABLE 5

Design Summary of Wall-Mounted Wick Combustors

|  | A | B | C |
|---|---|---|---|
| Fuel Loading (kg) | 0.62 | 0.048 | 5.42 |
| Diameter (mm) | 101 | 43 | 156 |
| Length (mm) | 241 | 508 | 1003 |
| Active Wick Length (mm) | 89 | 432 | 292 |
| Wick Aspect Ratio | .9 | 10.1 | 1.9 |
| Wick | 1 layer 16 mesh at wall plus 1 layer 40 mesh | 2 layers 100 mesh | 2 layers 100 mesh |
| Materials | Type 316 SS throughout | | |

TABLE 6

Summary of Wall-Mounted Wick Combustor Tests

| TEST | DURATION (h) | MAX. WALL TEMP. (K) | MAX. WICK POWER DENSITY (kW/m$^2$) | FUEL UTILIZATION (%) |
|------|------|------|------|------|
| Combustor A | | | | |
| 1 | 3.5 | 1323 | 173 | 70 |
| 2 | 2.1 | 1233 | 91 | |
| 3 | 1.6 | 1278 | 90 | 94 |
| 4 | 1.0 | 1293 | 50 | |
| 5 | 1.8 | 1283 | 213 | 91 |
| Combustor B | | | | |
| 6 | 0.5 | 1283 | 32 | 81 |
| 7 | 0.8 | 1316 | 30 | |
| 8 | 0.4 | 1255 | 70 | |
| 9 | 0.3 | 1375 | 88 | 79 |
| 10 | 0.8 | 1247 | 112 | 99 |
| Combustor C | | | | |
| 11 | 0.6 | 1220 | 15 | |
| 12 | 8.5 | 1200 | 15 | |
| 13 | 3.1 | 1210 | 34 | |
| 14 | 8.3 | 1200 | 25 | |
| 15 | 8.3 | 1230 | 101 | |
| 16 | 7.0 | 1255 | 57 | 93 |

These characteristics are indicative of a diffusion flame as the mechanism of combustion. Additional tests were conducted so that the combustion process could be observed [5]. The results substantiated the diffusion flame mechanism and provided methods for predicting the rate of reaction as a function of combustor conditions. It was also shown that the product condenses in a dropwise manner on the wick surface, covering less than 10% of the surface area.

Temperatures along the heat exchanger surfaces were found to be relatively nonuniform, particularly for the large aspect ratio (ratio of active wick length to diameter) combustors [7]. This was, in part, due to the heat transfer characteristics of the outside surface of the combustor. Another factor, however, is the mixing pattern of the oxidizer flow within the reaction space. Little is known about this aspect of combustor operation.

### 5.4 Conclusions

The conclusions of this portion of the study may be summarized as follows:

1. The wall-mounted wick combustor is a reliable system that is capable of long term operation at variable load. The system can be restarted. Fuel utilization is generally in excess of 93%.

2. The tests demonstrated wick power densities as high as 213 kW/m$^2$, and active wick heights of 432 mm. Conventional heat pipe design procedures can be used for wick design.

3. Combustor pressures and the temperature of the inside surface of the wick are related through the vapor pressure relation for lithium.

4. Large aspect ratio combustors yield relatively nonuniform wall temperatures due to variations in the heat transfer characteristics of the combustor and reaction rate variations as a result of the mixing pattern within the reaction zone.

5. The design is somewhat inflexible since all heat exchanger surfaces must be covered with wicking. This generally leads to relatively large reaction spaces, reducing system compactness. The wick is also difficult to replace.

PRESSURE (PA)

2

VAPOR PRESSURE OF LITHIUM

VAPOR PRESSURE OF LITHIUM-
LITHIUM FLUORIDE MIXTURE

$10^4$

8

6

4

2

PRESSURE ERROR BAR

| SYMBOL RUN | BURNING RATE (kg/m -s) | WICK L/D |
|---|---|---|
| ◁ 3 | .0005 - .0019 | 0.9 |
| ◁ 3 | .0019 - .0033 | 0.9 |
| ◀ 3 | .0033 - .0047 | 0.9 |
| ▽ 4 | .0005 - .0019 | 0.9 |
| ▼ 4 | .0019 - .0033 | 0.9 |
| ▷ 5 | .0005 - .0019 | 0.9 |
| ▶ 5 | .0075 - .0116 | 0.9 |
| △ 6 | .0005 - .0019 | 10.5 |
| ○ 7 | .0005 - .0019 | 8.6 |
| ○ 10 | .0009 | 5.7 |
| ● 10 | .0047 - .0054 | 5.7 |
| □ 13 | .0002 - .0010 | 1.8 |
| ● RATE TESTS | .0118 - .0920 | 0.5-2.0 |

$10^3$

8

6

4

.70   .74   .78   .82   .86   .90   .94

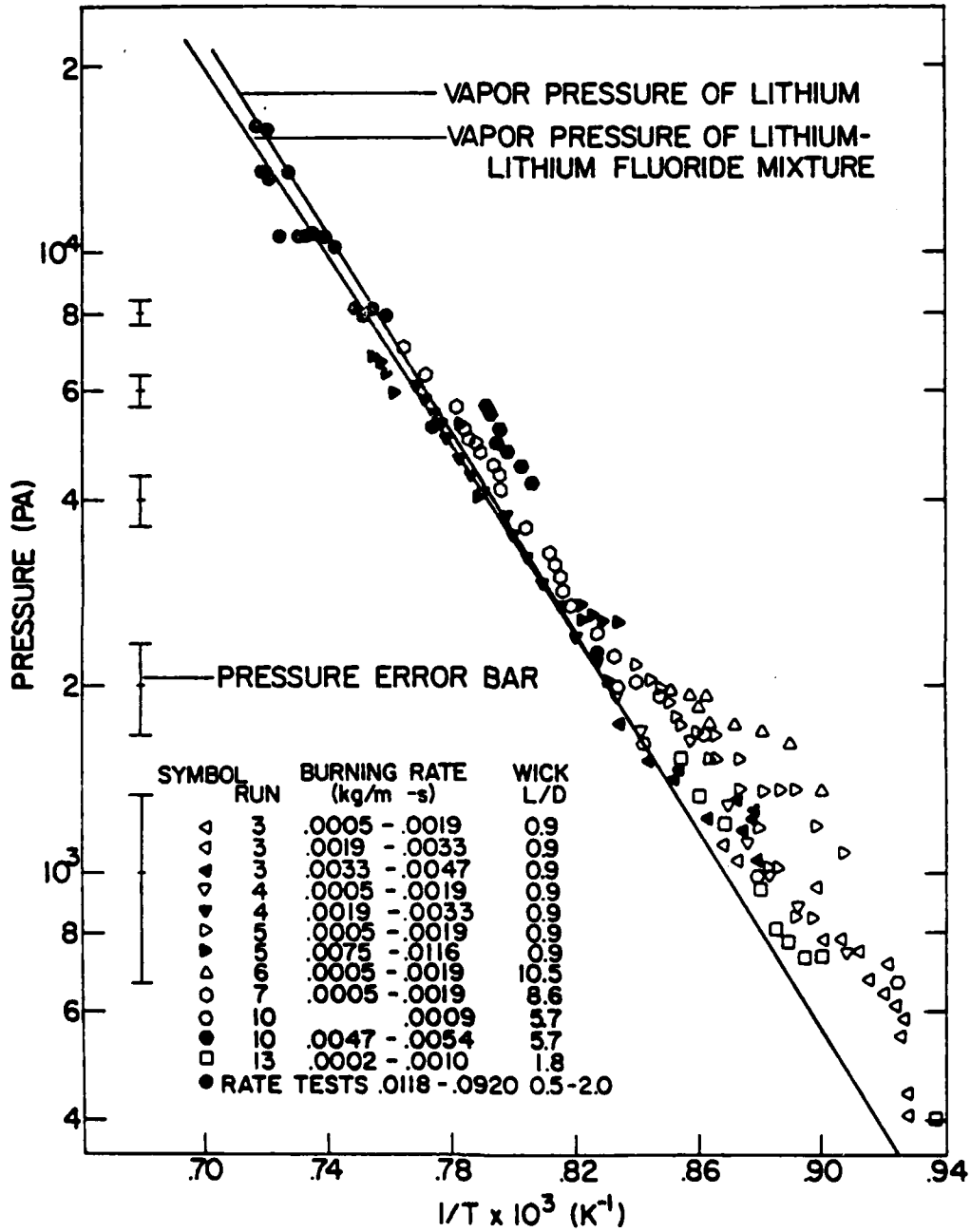$1/T \times 10^3$ $(K^{-1})$

Figure 14   Combustor pressure as a function of wick surface temperature

## 6. Reactive-Heat-Pipe Combustor

### 6.1 Introduction

The reactive-heat-pipe was a modification of the wall mounted-wick combustor. This concept provides greater flexibility for heat exchanger layout, greater compactness, more uniform temperature distributions on the surfaces of the heat exchanger, and simplifies wick replacement.

The objectives of the study of this concept were as follows:

1. Demonstrate the feasibility of the concept, considering long term variable load operation, restarting, fuel utilization, and wick power density limitations.

2. Determine the design characteristics of the wick and the heat transport system.

Further details on this portion of the investigation are reported in Refs. 6, 7, 10 and 11.

### 6.2 Test Apparatus

Two combustors were employed for the reactive-heat-pipe tests, a single injector unit having a thermal power of 7.5 kW, and a larger two injector unit having a thermal power of 15 kW. The smaller unit was used for initial feasibility tests of the concept. A summary of the design of this combustor is given in Table 7.

The 15 kW combustor was used to examine a more practical, multi-injector configuration of the reactive-heat-pipe. A summary of this design is given in Table 8. Cross-sectional views of the combustor appear in Figs. 15 and 16. Batch-type operation was employed with the fuel and combustion products being stored in the lower half of the combustor body. Refueling procedures will be discussed later. The combustion chamber and heat exchanger comprise the upper half of the combustion chamber. Naturally, this distribution of volume is arbitrary, and was chosen for convenience in the present tests. Most practical systems would involve a much larger proportion of the combustor for fuel and product storage.

Each injector/wick assembly had a design wick power density of 250 kW/m². The wicks were actually designed for higher power densities, and the system could be operated on one wick at a power density of 500 kW/m². The wick design procedures are described elsewhere [6]. The wicks were free-standing, spot-welded at the top to circular risers which formed the injector mount. The injector design was similar to the arrangement employed for the wall-mounted wicks.

TABLE 7

Design Summary of 7.5 kW Reactive-Heat-Pipe

| | |
|---|---|
| Fuel Loading | 0.89 kg |
| Maximum Thermal Power | 7.5 kW |
| Combustor Dimensions | 128 mm diameter, 270 mm long (uninsulated) |
| Wick Diameter | 73 mm |
| Active Wick Length | 125 mm |
| Wick Aspect Ratio | 1.7 |
| Wick | 2 layers, 100 mesh |
| Start System | electrical heater |

TABLE 8

Design Summary of 15 kW Reactive-Heat-Pipe

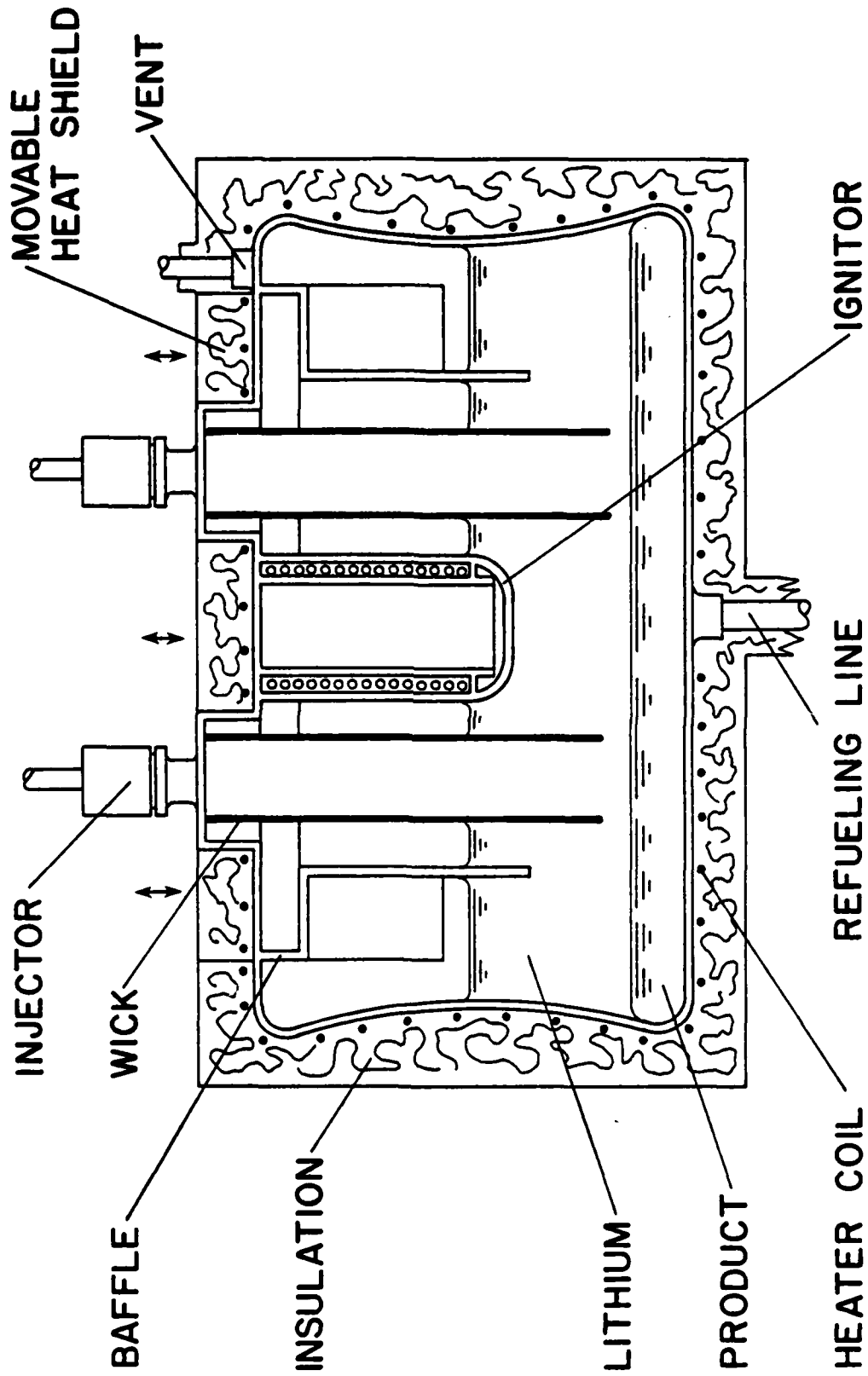| | |
|---|---|
| Fuel Loading | 6 kg |
| Combustor Dimensions | 273 mm diameter, 521 mm long (uninsulated) |
| Number of Wick/Injector Assemblies | 2 |
| Wick | 2 layers, 100 mesh |
| Wick Diameter | 56 mm |
| Active Wick Height | 160 mm |
| Aspect Ratio | 2.9 |
| Start System | electrical heater |

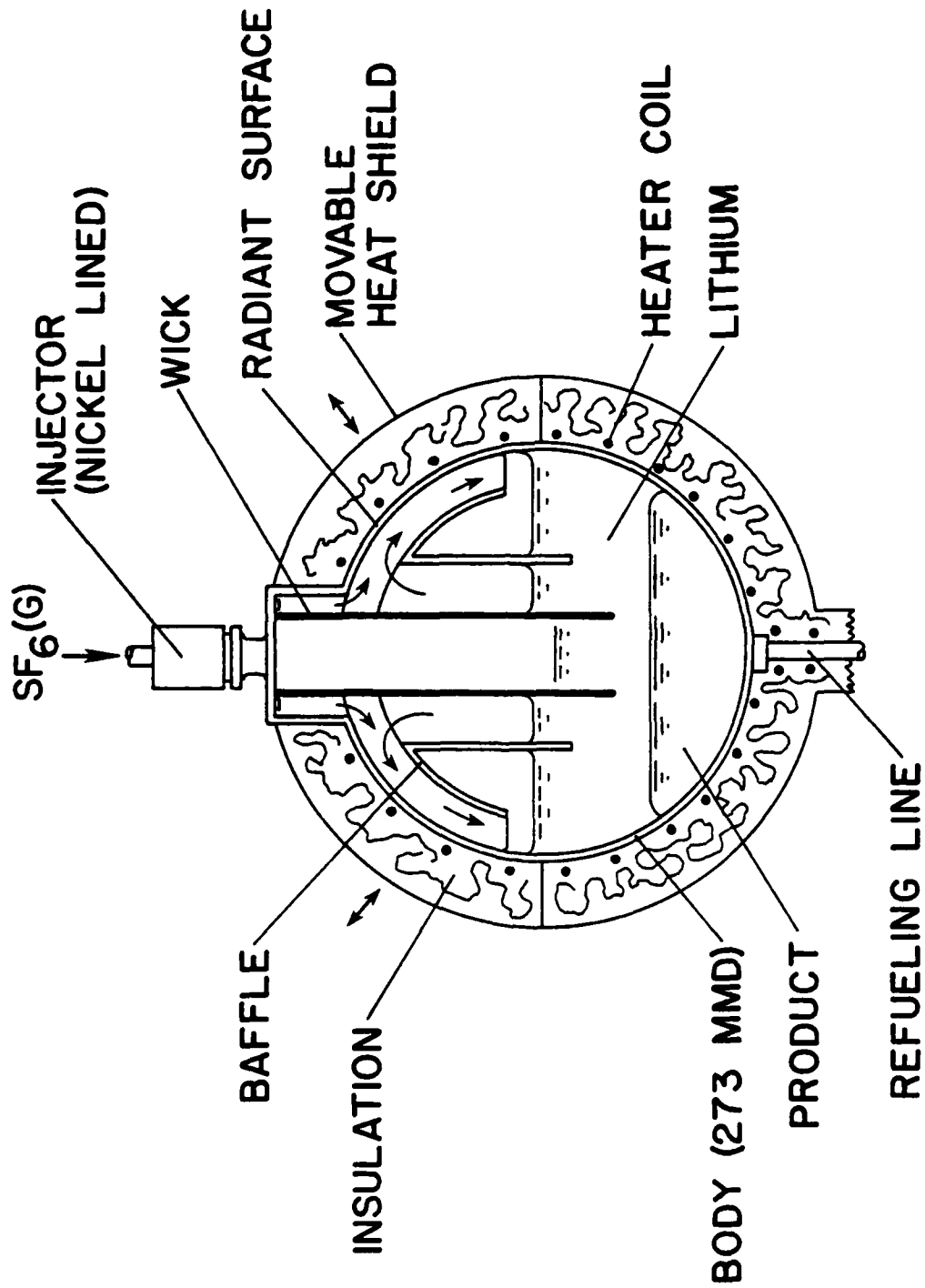Figure 15  Side view of the reactive-heat-pipe combustor

Figure 16 End view of the reactive-heat-pipe combustor

All components were fabricated from type 316 stainless steel, except for the nickel 200 liner of the injector passage. The outer surface of the combustor was used as the heat exchanger, transferring heat to the test cell by convection and radiation. The thermal load was varied by changing the position of heat shields over the surface of the heat exchanger. A baffle was placed along the inner side of the heat exchanger surfaces. This directed the flow of lithium vapor leaving the outside surface of the wick along the surface, driving noncondensibles into the ullage spaces of the combustor. The use of the baffle substantially improved heat exchanger performance when low levels of noncondensibles were present in the system.

The combustor was ignited by raising its temperature with electrical heaters located under the insulation. A heated well was also provided to increase the rate of heat transfer to the region of the wicks.

The combustor was refueled through a line at the bottom. A vent was provided so that noncondensibles could be removed from the condenser portion of the heat-pipe.

The gas supply system was similar to the arrangement used for the wall-mounted wick combustors. Each injector/wick assembly had a completely independent gas supply. Reaction space pressures were measured at the inlet of each injector. The entire system was leak checked with a helium leak detector prior to operation.

## 6.3 Refueling

Although the combustor was operated as a batch process, in situ refueling provided a capability for indefinite operating times, similar to a steady combustor. The arrangement for removing products of reaction is illustrated in Fig. 18.

Fueling began by placing the required amount of lithium in a separate tank which was heated to about 525 K, under argon. The refueling line was connected to the combustor and also trace heated to 525 K, as was the combustor itself. At this point the combustor was filled with argon provided by a continuous purge flow which was vented to the test cell. Once the entire system was heated, the lithium was transferred to the combustor by pressurizing the surface of the liquid in the fuel supply tank with argon. The lithium reached a common level in the combustor and the supply line at which time trace heating of the line was terminated. The lithium in the line then solidified, sealing the combustor. The transfer line was then disconnected and capped.

With the combustor filled with fuel, the wicks were wetted and the fuel was degassed. This was done in two separate operations. With the combustor under argon, it was heated to 1140 K, which was sufficient for the wicks to become wetted by capillary action. The combustor was then cooled to room temperature.
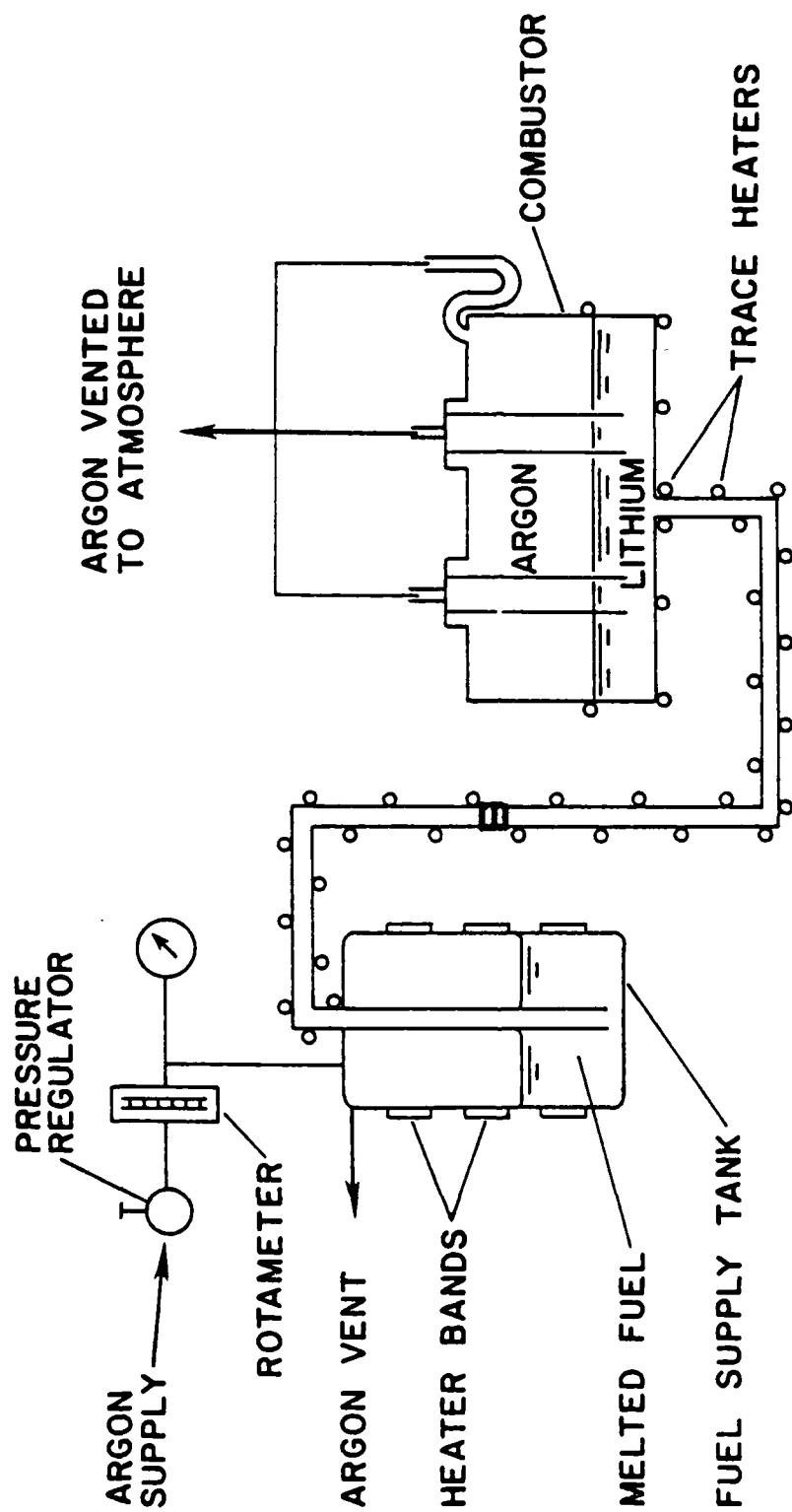
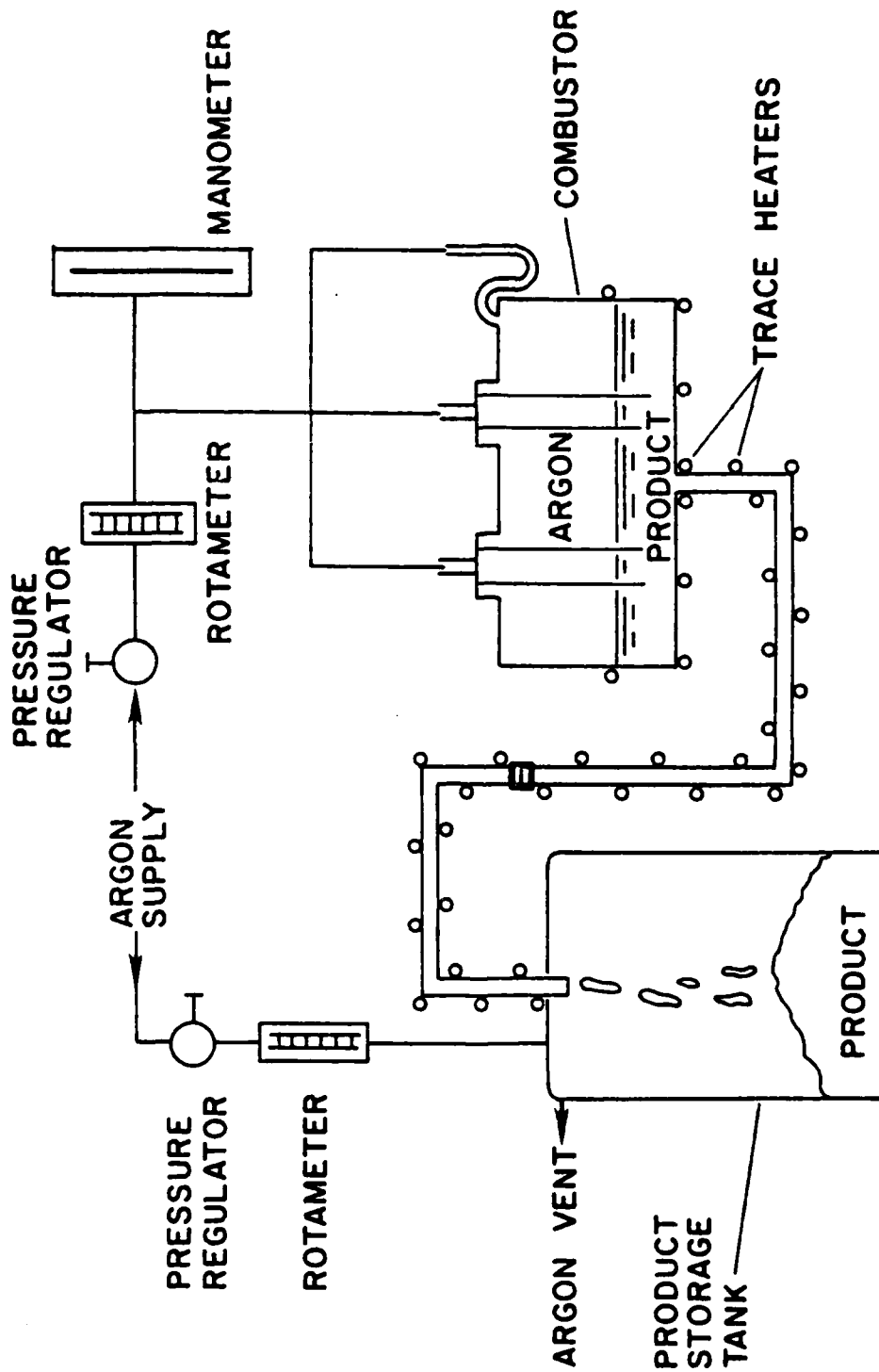Figure 17  Fueling arrangement

Figure 18  Product removal arrangement

Degassing was usually accomplished while heating the combustor for a test. Both injectors and the vent were connected to a vacuum pump and the combustor was heated to 920 K. The vacuum was then disconnected from the injectors and heating was continued. As the temperature rose, increasing quantities of lithium vapor would be drawn into the vent line where condensation would take place. Eventually the condensate would seal the trap and vacuum pumping could be discontinued.

The arrangement for emptying the combustor is illustrated in Fig. 18. The transfer line was connected to a product storage tank and trace heated to 1140 K. The combustor was also heated to this level to insure that the product was melted. The product collection tank and the combustor were both under argon, vented to the room through purge lines. The product was then transferred by pressurizing the surface of the liquid in the combustor. Once the product was transferred, the system was allowed to cool and the transfer line was disconnected and capped. The combustor could then be opened for inspection.

The wicks were removed for inspection by cutting through the risers on the injector/wick assemblies. The wicks were replaced by rewelding the riser.

## 6.4 Test Results

The reactive-heat-pipe tests are summarized in Table 9. Six tests were run with each combustor configuration. In general, operating periods were of 3-4 h duration, ended when test objectives were met. Operation was at heat exchanger temperature levels of 1200 K. The combustors could be restarted, and the larger unit was routinely refueled as described in the previous section. Each time that high fuel utilization was sought, fuel utilization efficiencies in excess of 95% were achieved.

Figure 19 is an illustration of power output, wall temperatures and injector pressures during test 5. The combustor was operated with both injectors at equal power levels. The combustor was kept at idle, with the heat shields closed, until operating temperatures were reached. Operation was then at twenty minute periods of half power, full power, idle and full power. The remainder of the test was spent at half-power, until fluctuating pressures indicated possible fuel depletion. The test was terminated at 95% fuel utilization to prevent possible damage to the wicks.

The temperature plot in Fig. 19 shows the condenser and bath temperatures. This test was a restart, and the condenser temperature was higher than the bath, in the early portions of the test, until the product remaining from test 4 became heated. Once heating was complete, the insulated bath area remained at a slightly higher temperature level than the heat exchanger.

The combustor pressures illustrate the variation of pressure with wick temperature. At high power levels, wick temperatures are highest, causing a commensurate increase in combustor pressure.

-43-

TABLE 9

Summary of Reactive-Heat-Pipe Tests[a]

| TEST | DURATION (h) | MAXIMUM WICK POWER DENSITY ($kW/m^2$) | MAXIMUM FLOW POWER DENSITY ($MW/m^2$) | FUEL UTILIZATION (%) |
|---|---|---|---|---|
| 7.5 kW unit | | | | |
| 1 | 4.3 | 45 | .3 | 34 |
| 2 | 4.2 | 260 | 1.8 | 96 |
| 3 | 3.1 | 260 | 1.8 | 97 |
| 4 | 3.2 | 260 | 1.8 | 100 |
| 5 | 3.0 | 260 | 1.8 | |
| 6[b] | 1.3 | 87 | .6 | 95 |
| 15 kW unit | | | | |
| 1 | 1.1 | 310 | 3.5 | |
| 2[b] | 4.6 | 290 | 3.1 | |
| 3[b] | 2.4 | 350[c] | 3.9 | 72 |
| 4 | 4.1 | 220 | 2.3 | |
| 5[b] | 3.9 | 220 | 2.3 | 95 |
| 6[b,d] | 2.5 | 440[c], 310[c] | 5.0, 3.5 | |

[a] Operating temperatures near 1200 K

[b] Restart

[c] Wick burnout condition

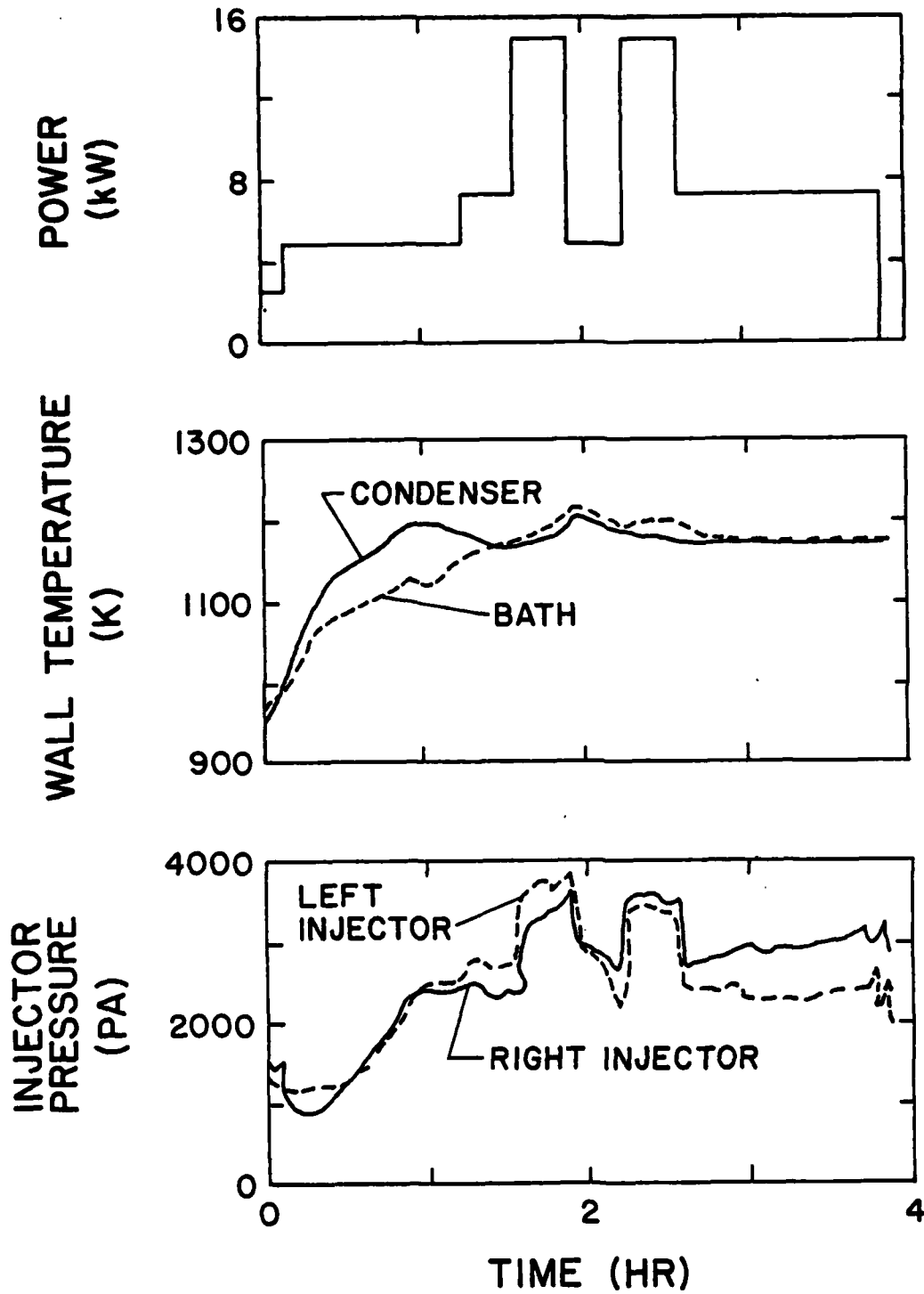[d] Arterial wick configuration, four 1 mm diameter arteries

Figure 19 Typical reactive-heat-pipe test results

Heat pipe action provides very uniform temperature distributions on the heat exchanger, as long as noncondensibles are controlled in the system. This is illustrated in Fig. 20. During test 4, insufficient time was provided to pump noncondensibles from the system and condenser action was poor. As the vapor flows towards the heat exchanger surfaces it displaces the noncondensible gas, much like a diffusion pump. The noncondensible blankets the edges of the baffle, reducing heat transfer rates and temperature levels in the radiative heat exchanger. When noncondensibles are properly removed, as in test 5, the vapor reaches all positions on the heat exchanger and the temperature distribution is uniform.

The maximum power density capabilities of the conventional wick arrangement were examined during test 3 with the 15 kW combustor. The power level of the combustor was increased in steps, with both injectors equally loaded, beyond the design power level of 15 kW. After a period of operation at 19 kW, a hot spot was detected on the wall of the ignitor tube, indicating wick burnout, and operation was terminated. When the wicks were inspected, one wick was found to have two holes in it, with corresponding corrosive damage of the adjacent surfaces of the combustion at positions aligned with these holes. The holes were approximately three quarters of the way from the liquid surface to the top of the wick. The other wick was in excellent condition. The average wick power density at the time of failure was 350 $kW/m^2$, the flow power density (defined as the energy generation rate per unit crossectional area of the reaction space) was 3.9 $MW/m^2$. The latter quantity is a measure of potential reaction nonuniformities over the wick surface, since high flow power densities imply high $SF_6$ transport rates to the wick surface, and thus high reaction rates, near the injector.

Normally, the critical region for wick dryout and corrosion would be expected to be near the top of the wick, since this point involves the greatest frictional and gravitational forces to be provided by the capillary forces of the wick. The design wick power density was 500-600 $kW/m^2$, which was somewhat greater than the measured failure condition. The results suggested that nonuniform reaction rates, coupled with operation near the limit of the pumping capabilities of the wick, caused a local region to become fuel starved, followed by dryout and corrosive failure. Subsequent tests with the conventional wick system, tests 4 and 5, were run at wick power densities of 220 $kW/m^2$ with no further problem with the wick (earlier work at 300 $kW/m^2$ and 3.1 $MW/m^2$ also gave no difficulties).

Reaction nonuniformity is a difficult problem, involving the hydrodynamics of the reaction space and the flow from the injector. Understanding of these processes is poor, therefore, the approach to obtaining higher power densities was to increase the pumping capability of the wicks, so that higher local reaction rates could be sustained without dryout. This also provided an opportunity to examine the potential of more effective wick arrangements for the reactive-heat-pipe.
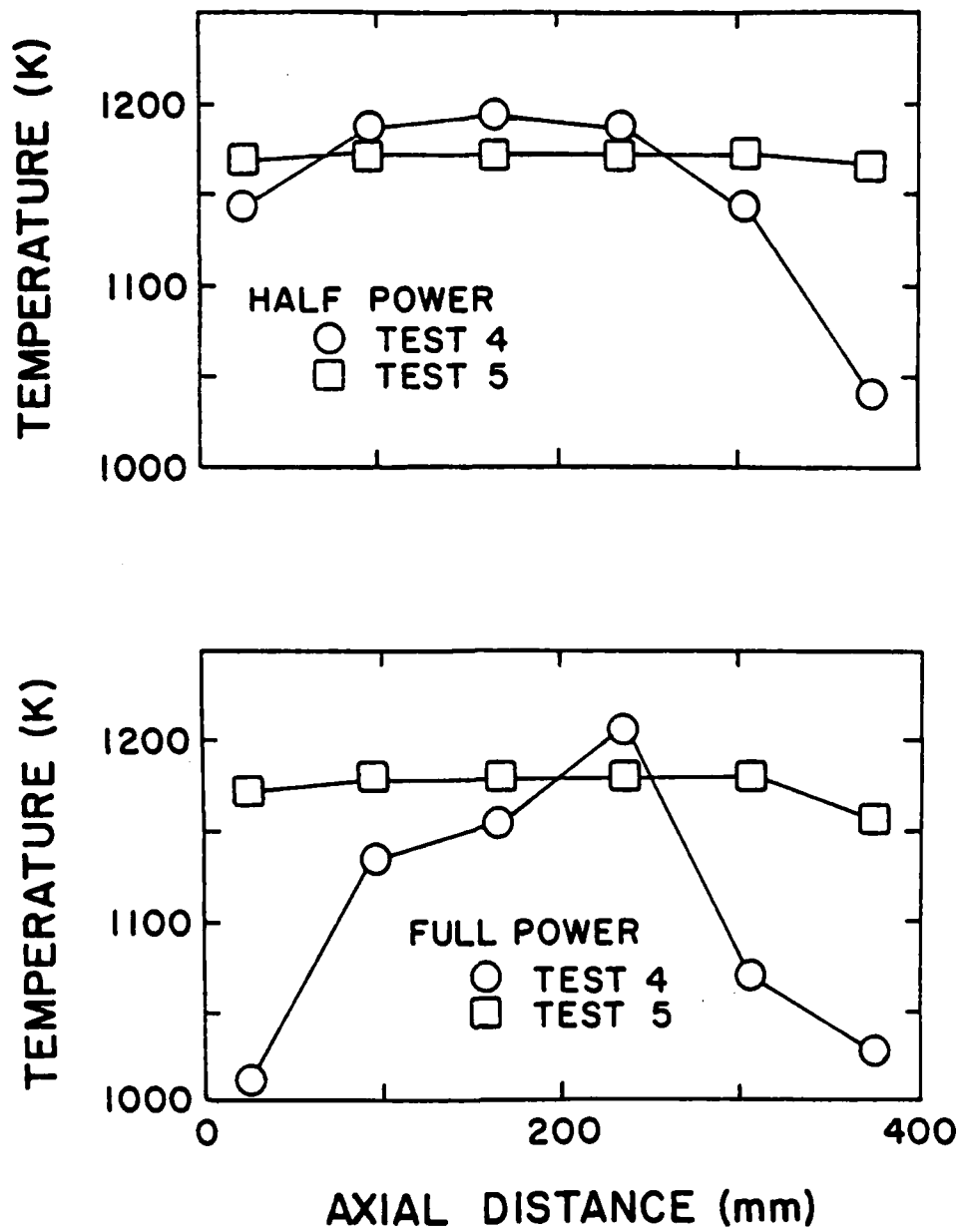
Figure 20  Axial temperature distributions along the heat exchanger

Improved wick pumping capabilities were obtained by the use of arterial wicks. A crossection of the arterial wick configuration is illustrated in Fig. 21. In this case, the liquid can flow vertically in arteries, which have a relatively large crossection, as well as through the wick itself. The frictional pressure drop can be reduced, substantially increasing pumping capabilities over conventional wicks.

Design procedures for arterial wicks of given pumping capabilities, applied to the reactive-heat-pipe, are described in Ref. 11. One additional requirement for arterial wicks is that they be capable of self priming, i.e. filling with liquid to the top of the artery passage when the lower edge of the wick is placed in liquid. Procedures for selecting artery sizes to meet this requirement are discussed elsewhere [11, 23].

Arterial wicks were designed for the 15 kW combustor. Each wick employed four arteries equally spaced, having diameters of 1 mm. Self-priming to a height of 300 mm was demonstrated. The arterial wicks had a design pumping capability in excess of 4000 kW/m$^2$.

Test 6 considered the power density capabilities of the arterial wick arrangement. The two wicks were operated independently, providing two measurements of the maximum power densities. Once burnout was detected, by observing a hot spot on the combustor, the failed wick was placed at idle, which prevented corrosion damage to the combustor. The maximum power densities are given in Table 9, the values are not a significant improvement over the conventional wick in spite of a pumping capability almost an order of magnitude higher for the arterial wicks. The holes in the wick were near the top, between the arteries.

The results suggest that flow power density is the limiting factor, with satisfactory operation demonstrated at values below 3.1 MW/m$^2$. Further study would be required, however, to establish the limitations for other configurations. In particular, higher values of flow power density might be possible with lower wick aspect ratios (which tends to provide more uniform reaction rates [5]). Variations in the diameter of the injector flow passage and the diameter of the wick may also be a factor.

## 6.5 Conclusions

The reactive-heat-pipe concept was developed as a means for conducting the Li-SF$_6$ reaction, and conveniently transporting the heat of reaction to a thermal load. The conclusions of the study can be summarized as follows:

1. Operation of the reactive-heat-pipe was demonstrated over long durations with variable thermal load, including idle.
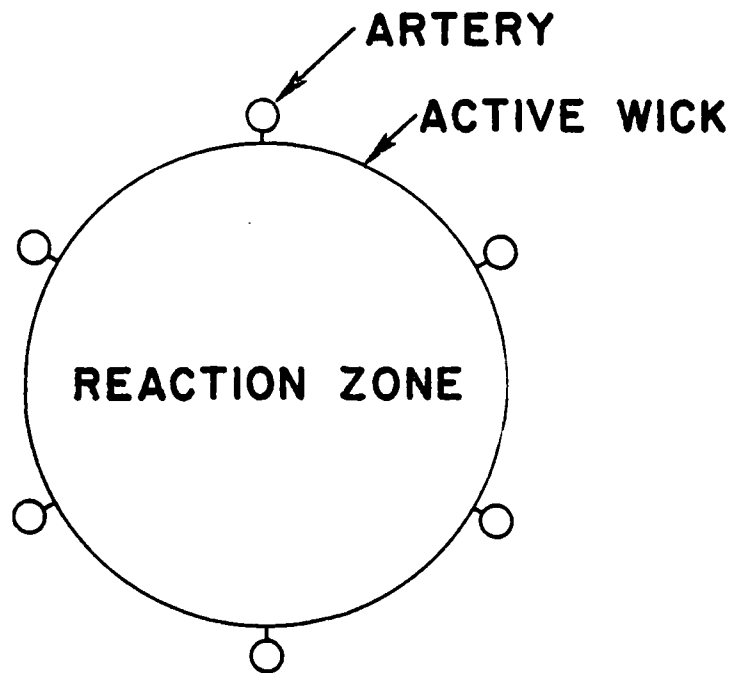
Figure 21   Arterial wick arrangement

2. Reactive-heat-pipes were operated in a batch mode. However, in situ refueling procedures were developed so that operation was essentially independent of the fuel inventory of the combustor, similar to steady combustor operation.

3. The reactive-heat-pipe leads to more compact arrangements than the wall-mounted wick combustor, since the ullage space can be utilized for the heat exchanger. The system provides inexpensive heat-pipe action, leading to uniform heat exchanger surface temperatures, which simplifies heat exchanger design. Wick replacement is more convenient for the reactive-heat-pipe.

4. Each time that high fuel utilization was sought, more than 95% of the fuel initially plaxed in the combustor was consumed.

5. As long as liquid fuel can be supplied to the wick, only the wick must be heated to ignite the combustion process. Wick ignition was generally achieved at 920 K. Lower temperature levels might be possible for ignition but this was not examined during this investigation. Once ignited, wick operation is essentially independent of bath temperature levels, providing fast response and rapid start capabilities due to the relatively small heat capacity of the wick.

6. Satisfactory operation of the wick was observed at flow power densities as high as 3 $MW/m^2$ for the present wick configurations. Higher values may be possible by reducing the aspect ratio of the wick and adjusting the injector geometry, however, these effects need to be established.

7. The use of arterial wicks provides substantial increases in potential wick power densities over conventional wicks (a factor of 8 increase was demonstrated during the present investigation). Using arterial wicks, wick power densities in excess of 1 $MW/m^2$ can be anticipated.

8. Good condenser action requires control of noncondensibles in the system. This was accomplished by degassing the fuel and providing baffles over the heat exchanger surfaces during the present investigation. No introduction of noncondensibles as contaminants by the flow of $SF_6$ was detected during the study.

9. Wick-type combustors are quiet, since the liquid within the combustor is not agitated. The systems proved to be very safe to operate Test personnel were routinely in the area of the combustors to observe operation during the tests. Fault conditions, including air leakage into the system, were readily controlled by terminating the flow of $SF_6$, backfilling the system with argon, and allowing the combustor to cool.

## 7. Safety Considerations

The present study did not specifically deal with the safety characteristics of Li-SF$_6$ combustion systems. Some experience was obtained having a bearing on safety characteristics, however, which is discussed in the following. References 28-30 provide a more comprehensive treatment of safe handling considerations for lithium and sulfur-hexafluoride.

Sulfur-hexafluoride is a colorless and odorless gas. Similar to carbon dioxide, it is nonflammable and nontoxic. However, the material can act as a simple asphyxiant, by diluting air sufficiently to result in an oxygen deficiency [24, 25]. A threshold limit value of 1000 ppm was established for this material in 1968 (concentration in air to which nearly all workers may be repeatedly exposed during an 8-hour working day without adverse effects). The test area used during the present study was sufficiently open so that no special precautions were required for handling sulfur-hexafluoride.

Lithium reacts with oxygen, nitrogen and water vapor in the air [26]. In order to avoid contamination of the metal, it is normally stored and handled under an inert gas, frequently argon. During the present investigation, lithium was received from the manufacturer as 25 mm diameter rods, packed in air-tight cans under argon.

The rate of reaction of lithium with air is relatively slow at room temperatures. Therefore, brief exposure to air, e.g. adding lithium to a fuel tank, etc., was acceptable during the present study. The material was handled with gloves to avoid contamination by moisture on hands. It was occasionally necessary to handle the material for longer periods of time. Such operations were done in a controlled atmosphere chamber, under argon (CP grade).

All operations with lithium at temperatures above room temperature were done either under vacuum or argon. A purge flow of argon was maintained on all systems vented to the atmosphere. With increasing temperature, the vapor pressure of lithium increases, causing purge flows to entrain increasing concentrations of lithium vapor [4]. Upon cooling, the vapor condenses into small lithium particles, which react upon contact with the atmosphere. Since lithium vapor pressures are relatively low at typical system temperatures [4], the energy released by reaction is negligible in comparison to the sensible heat of the purge flow. However, the small reaction product particles irritate the respiratory system if inhaled. Therefore, all purge flows were vented to the laboratory ventilation system or a fume hood.

In order to avoid spills of high temperature lithium, care must be taken with welding of combustor components. Threaded connections under the surface of the liquid were avoided for systems operating for long durations. Weld integrity was tested in vacuum systems by

helium leak checking the system, at operating temperatures, before
filling with fuel. Methods of fabrication, precleaning, cleaning,
etc., for systems containing lithium are covered by Mausteller, et al.
[26]. In case of spills, laboratory areas were equipped with a solid
fire extinguishing agent for lithium, Pyrene G-1 powder, although
other materials are also available [26]. Drip pans with the bottom
covered with Pyrene G-1 were also employed as an extra precaution,
during laboratory use, in areas where spills might occur.

Combustors were emptied for refueling by pressure-pouring the
molten contents, heated to 1140 K, as described in Section 6.3.
Any unburned lithium within the combustor is also transferred with
the product. Therefore, due to the high temperature level of the
material, safe transfer requires that the product storage tank be
filled in an inert gas. Argon was used for this purpose during the
present study, with a purge flow maintained to the atmosphere.

When hot product flows into the storage tank, argon within the
tank becomes heated. The vent in the tank must be adequately sized
to allow sufficient outflow of argon so that the storage tank does
not become pressurized which would inhibit the outflow of product
from the combustor. The heated argon leaving the storage tank
contains lithium vapor and should be handled similar to other vent
flows.

The reaction products have the composition (molar) 83.3%
lithium fluoride and 16.7% lithium sulfide. The product can also
contain quantities of unreacted lithium, as noted earlier. Upon
contact with air, the product reacts to form a gas which is toxic
above 50 ppm in air. Therefore, it was found most convenient to
store reaction products in sealed containers in a well-ventilated
area. Ultimate disposal followed standard chemical waste procedures
for this laboratory.

## 8. Recommendations

The objective of this investigation was to develop Li-SF$_6$ combustion systems capable of long duration, variable load operation. The units were to be capable of reuse and refueling, and were to operate totally sealed from the surrounding environment. Other desirable features included a restart capability and fast start and fast response to changes in the thermal load. Potential reliability and safety were also factors.

Of the combustor types considered during this investigation, the wick-type combustors demonstrated the greatest potential for meeting these objectives. Based on potential cost, compactness and the simplicity of the heat exchanger interface, the reactive-heat-pipe is the most promising of these arrangements.

Further investigation of several aspects of reactive-heat-pipe operation is required, before practical designs can be undertaken, as follows:

1. The effect of aspect ratio and injector geometry on flow power limitations, due to nonuniform reaction rates, should be investigated. Only in this manner can the full wick power density capabilities of arterial wicks be achieved.

2. Improved ignition methods should be considered, so that fast start-restart capabilities can be developed.

3. Improved materials should be examined for combustor and wick construction in order to provide increased creep strength at high temperatures in comparison to type 316 stainless steel which was used in the present investigation.

4. Improvements should be made in the injector cooling system used in the present investigation. The use of a liquid metal heat pipe surrounding the injector passage is an attractive approach to injector cooling [16].

5. The effect of wick orientation on system performance should be examined, only vertical wicks were considered in the present investigation.

6. At very high wick power densities, the displacement of liquid under the reaction zone becomes a limiting factor in design. If the lower part of the wick were fitted with a trap, molten product would become the liquid seal for the reaction zone. Due to its higher density, the liquid displacement could be significantly reduced by this arrangement. Such a system would essentially be a steady reactive-heat-pipe.

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